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# FINAL REPORT

# ANALYSIS OF SATELLITE DATA ON ENERGETIC PARTICLES OF IONOSPHERIC ORIGIN

Contract NASw 2777

Period of Performance: 24 March 1975 through 23 March 1976


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## INTRODUCTION

This is the final report on a program for the analysis of selected data from the Lockheed Energetic Ion Mass Spectrometer experiment on satellite 1971-89A, with emphasis on the morphology of the $O^+$ ions of ionospheric origin with energies in the $0.7 \leq E \leq 12$ keV range that were discovered with this experiment.

## RESULTS

The principal result of this program has been the completion of a detailed statistical study of the properties of precipitating $O^+$ and $H^+$ ions during two principal magnetic storms. The results of this study are described in two papers which have been submitted to the Journal of Geophysical Research and are included as Appendices A and B of this report. In addition to this work, three studies have been initiated into other aspects of the morphology of the energetic $O^+$ ions, and substantial progress on these studies has been made.

1. Dr. E. G. Shelley has begun an investigation of the $O^+$ ions observed precipitating into the dayside cusp. These ions are interpreted to result from a quasi-trapped population of $O^+$ ions on closed field lines which convect poleward into the cusp a substantial distance before they are emptied of their contents by precipitation or discharge into interplanetary space. A quantitative study of the observed latitudinal distribution of the $O^+$ ions in the cusp has indicated that they probably are trapped over a substantial range of equatorial pitch angles including relatively large angles, thus implying that they may form a significant portion of the ring-current



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ion population. These preliminary results were presented by Dr. Shelley at the Advanced Study Institute on Magnetospheric Particles and Fields at Graz, Austria, in August 1975.

2. Dr. R. G. Johnson has initiated a study of the energetic $O^+$ ion morphology during magnetospheric substorms as distinguished from magnetic storms. He finds that the $O^+$ ion peak intensities are correlated with the AE index during two substorms studied. Some preliminary results of this work were discussed in an invited review paper presented by Dr. Johnson at Kiruna, Sweden, and in a contributed presentation at the San Francisco meeting of the American Geophysical Union in December 1975. The text of the review paper and the abstract of the contributed presentation are included in the appendices.

3. The Explorer 45 satellite was operating in the equatorial plane during the period of the 1971-89A experiment at low altitudes and simultaneous data were acquired on many occasions. We have initiated a joint study with Dr. Bodo Parady of the University of California at Berkeley to investigate the relationship between low-frequency electromagnetic emissions observed on Explorer 45 and the $O^+$ ions observed on 1971-89A.

## PUBLICATIONS

### Written Papers

"The Morphology of Energetic $O^+$ Ions during Two Magnetic Storms: Temporal Variations," by R. D. Sharp, R. G. Johnson, and E. G. Shelley, submitted to Journal of Geophysical Research, 1975.

"The Morphology of Energetic $O^+$ Ions during Two Magnetic Storms: Latitudinal Variations," by R. D. Sharp, R. G. Johnson, and E. G. Shelley, submitted to Journal of Geophysical Research, 1975.

"Composition of the Hot Plasmas in the Magnetosphere," by R. G. Johnson, R. D. Sharp, and E. G. Shelley, in Physics of the Hot Plasma in the Magnetosphere, edited by B. Hultqvist and L. Stenflo, Plenum Publ. Corp., New York, 1975, pp. 45-68.

Contributed Presentations

"Observations of Energetic $O^+$ Ions within the Low-Altitude Dayside Cusp," presented by E. G. Shelley at the Advanced Study Institute on Magnetospheric Particles and Fields, Graz, Austria, 4-5 August 1975.

"The Morphology of Energetic $O^+$ and $H^+$ during Two Magnetic Storms (abstract)," by R. D. Sharp, R. G. Johnson, and E. G. Shelley, EOS Trans. Am. Geophys. Union, Vol. 56, 434, 1975.

"Satellite Observations of Energetic $O^+$ Ions during Two Magnetic Substorms (abstract)," by R. G. Johnson, R. D. Sharp, and E. G. Shelley, EOS Trans. Am Geophys. Union, Vol. 56, 1048, 1975.

Invited Presentations

"Composition of the Hot Plasmas in the Magnetosphere," presented by R. G. Johnson at the Nobel Symposium on the Physics of the Hot Plasma in the Magnetosphere, Kiruna, Sweden, April 1975.

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APPENDIX A

# THE MORPHOLOGY OF ENERGETIC $O^+$ IONS DURING TWO MAGNETIC STORMS: TEMPORAL VARIATIONS

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(Revised January 1976)

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# THE MORPHOLOGY OF ENERGETIC $O^+$ IONS DURING TWO MAGNETIC STORMS: TEMPORAL VARIATIONS

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## ABSTRACT

A study has been conducted of the morphology of precipitating $O^+$ and $H^+$ ions in the energy range $0.7 \le E \le 12$ keV during the storm-time period from December 16-18, 1971, which encompassed two principal magnetic storms. This paper describes some of the results of this study with emphasis on the temporal variations of parameters characterizing the intensity, average energy, and spatial location of the zones of precipitation of the two ionic species. One of the principal results was the finding that the intensity of the precipitating $O^+$ ions was well correlated with the geomagnetic indices which measure the strength of magnetospheric substorm activity and the strength of the storm-time ring current. Since the $O^+$ ions are almost certainly of ionospheric origin the correlations indicate that a previously unknown strong coupling mechanism existed between the magnetosphere and the ionosphere during the storm period. Some other morphological features apparent in the data are: 1) the storm-associated initial increase of the $O^+$ ions on the nightside (0300 LT) was found to lead that on the dayside (1500 LT) and lag the initial nightside $H^+$ increase by more than one hour in both

storms; 2) a strong correlation was observed between the variations in locations of the $O^+$ and $H^+$ precipitation regions on both the day and nightside crossings; and 3) the average energies of the $O^+$ and $H^+$ precipitations were significantly correlated on the dayside crossings. The implications of these results with respect to some phenomenological models of the $O^+$ morphology are discussed.

The total worldwide precipitated ion energy flux has been estimated during the period of the study and compared to the ring current energy content as measured by Dst. The comparison indicates that precipitation was an important loss mechanism for ring current ions with energies less than 12 keV during the December 17-18, 1971 magnetic storm.

## INTRODUCTION

The discovery of $O^+$ ions with energies of up to 12 keV in the magnetosphere was reported by Shelley et al. [1972]. Synoptic studies of several aspects of the morphology of these ions were described by Sharp et al. [1974], Shelley et al. [1974], and Johnson et al. [1975]. The energetic $O^+$ ions were inferred to be of ionospheric origin. They were observed in every storm studied over a one-year period and at all local times. They were also observed at reduced intensities during non-storm times. This is the first of two papers which will present more detailed results from a statistical study of the temporal and latitudinal variations of the $O^+$ ions and the accompanying protons in the same energy range ($0.7 \leq E \leq 12$ keV) during two magnetic storms. This paper will present integral parameters, each characterizing a single traversal of the precipitation zone. Paper II will describe the latitudinal variations averaged over each of the two storms. A similar statistical analysis of a comparable body of data on auroral electrons and the more energetic component of the auroral protons has been published [Sharp and Johnson, 1968; Sharp et al., 1969].

The two storms studied here occurred in the period December 16-18, 1971. Both were initiated with sudden commencements which occurred at 1904 UT on December 16 and 1418 UT on December 17. The first storm had only a small main phase with a peak Dst of 54γ. The second storm had a classic main phase with a peak Dst of 171γ and a recovery phase lasting until about 2300 UT on the 18th. The relevant geomagnetic indices characterizing this period are shown in Figure 1. Extensive data on the equatorial particle distributions during this same period were acquired by the Explorer 45 satellite [Smith and Hoffman, 1973; Hoffman, 1973; Williams and Lyons, 1974a,b; Lyons and Williams, 1975; and Williams, 1975].

The data presented here were obtained from an energetic ion mass spectrometer experiment on the low-altitude polar satellite 1971-089A. The experiment contained three spectrometers. Each consisted of an electrostatic analyzer in series with a crossed field velocity filter which provided both mass-per-unit-charge and energy-per-unit-charge information on the measured particles. The satellite was in an approximately circular orbit of 800 km altitude and 93° inclination. It was in the local time plane 0300-1500 during the period described here. The satellite was stabilized about three axes and the spectrometers were oriented at 55° to the local zenith so that they primarily sampled precipitating particles near the edge of the loss cone.

during their traversals of the auroral and sub-auroral regions. The nine energies per unit charge sampled by the experiment were 0.74, 1.01, 1.41, 2.14, 2.92, 4.07, 6.3, 8.6, and 12.1 keV. Mass-per-unit-charge scans at each of these values were obtained in 6.14 seconds. Representative mass-per-unit charge distributions are given in Shelley et al. [1972] which also contains a more detailed description of the experiment and preliminary results from this same storm-time period.

## ANALYSIS AND RESULTS

In order to investigate the variations in the properties of the ion fluxes on a time scale appropriate to the period of the storm, we have formulated a group of parameters based on the average or integral fluxes during a single complete traversal of the northern precipitation zone. This gives us a measurement in each of the northern precipitation zones (day and night) about every 100 minutes which is comparable to the time resolution of the various geomagnetic indices characterizing the disturbed period. To formulate these parameters for both the $O^+$ and $H^+$ ions we have summed the counts in the region of peak response in the mass-per-unit-charge sweep for each ion species and subtracted the background from an equivalent number of channels. Then for each six-second measurement cycle, we have computed the integral energy flux and average energy for each species in the energy range $0.7 \leq E \leq 12$ keV. For the intensity parameter, we have integrated the flux over the range in invariant latitude $44^\circ \leq \Lambda_L \leq 80^\circ$. For the hardness parameter we have computed the average energy of each ion species over the same interval. To characterize the location of the precipitation zone we have computed the invariant latitudes at which 10%, 50%, and 90% of the energy flux latitudinal integrals were reached.

The results for the northern hemisphere observations during the period 1200 UT on December 16 to 2400 UT on December 18, 1971 are presented in Figures 2 through 5. Figure 2 shows the integral energy flux values. They have been multiplied by the satellite velocity and corrected for the (generally small) deviations of the trajectory from meridians of magnetic longitude so that they are an approximation to the instantaneous value of the energy flux precipitating through a one-cm-wide slit aligned perpendicular to the precipitation zone. The error bars represent counting statistics only. There are additional experimental uncertainties, discussed by Shelley et al. [1972, 1975], which we estimate as approximately ± 35%.

One sees in Figure 2 that there is a general correspondence between the $O^+$ zone integrals and the magnetic activity indices shown in Figure 1 with large flux increases being observed shortly after the sudden commencements. The nightside (0300 LT) $O^+$ increase leads the dayside (1500 LT) increase and lags the $H^+$ increase by over an hour in each storm. On the nightside, the $O^+$ and $H^+$ intensity levels are generally comparable while on the dayside the $O^+$ precipitation is considerably weaker than the $H^+$ precipitation in this energy range.

Figures 3 and 4 show the zone average energy values. For Figure 3, we defined the average ion energy as the ratio of the zone integral energy flux to the zone integral number flux. For those cases where the latter was less than two standard deviations above zero the average energy values were not considered significant and were deleted. The error bars represent counting statistics only. This definition for the average ion energy tends to give the most weight to the intense precipitation events in each zone crossing. In order to evaluate the significance of the observed trends we defined the alternative hardness parameter shown in Figure 4. For this parameter we computed the average energy for each individual (six-second) spectral measurement that was considered statistically significant and then computed the grand average value of these quantities over the precipitation zone, weighing each measurement equally. The significance criterion chosen was that the integral number flux in the individual measurement had to be greater than twice its standard deviation. The error bars in this figure represent the standard deviations of the means of these individual average energies and not counting statistics. For those cases where less than ten individual measurements were included, the number of measurements, n, has been indicated on the figure. In examining Figures 3 and 4 we see that the average energies do not vary substantially between the two ion species or between the day and nightside measurements. There is a correspondence in the temporal variations of the $O^+$ and $H^+$ values on the dayside that can be seen in the lower panels of both Figures 3 and 4 so that we feel it is not the result of biasing due to a specific weighing technique.

The degree of this correlation is indicated quantitatively by the correlation coefficient between the two quantities. For example, the value of this coefficient computed for the 26 pairs of average energies with $n > 4$ in the lower two panels of Figure 4 is $r = 0.54$. The probability that such a sample of uncorrelated pairs would have a correlation coefficient this large is $\approx 0.005$. We will discuss the implications of this correlation in the next section.

Figure 5 shows the locations of the precipitation zones. The center of the region, measured by the invariant latitude of the 50% point of the zone integral energy flux, is indicated with a circle for $O^+$ ions and a square for $H^+$ ions. The horizontal bars represent the extent of the region as measured by the 10% and 90% points in the same parameter. In several instances during this period the proton precipitation extended above $80^\circ$ invariant latitude. The satellite orbit on some passes did not extend higher than $80^\circ$ so in order to form a uniform data base we truncated the zone integrals at that latitude. Thus for those points in Figure 5 in which the upper bar is in the vicinity of $80^\circ$, that point does not necessarily mark the upper latitude of the precipitation region. Despite this distortion we see a detailed tracking of the precipitation zones of the two types of ions on both the day and nightsides. There is a latitudinal displacement between the two species with the $O^+$ zone generally located equatorward of the $H^+$ zone by several degrees. There is a correlation between the results at the two local times as well as between the two ion species.

## DISCUSSION

As noted above in connection with Figure 2 the observed nightside $O^+$ fluxes are more intense than those on the dayside and there is a time delay in both storms between the initial $O^+$ increases on the night and daysides. This is suggestive of a longitudinal drift model with the principal injection occurring on the nightside. In the energy range of these measurements longitudinal drift is strongly affected by the corotation and convection electric fields. Shelley et al. [1974] showed from a study of the local time dependence of the $O^+$ ions that the median peak precipitated flux is about an order of magnitude higher in the LT interval 21-09 hours than it is in the interval 09-21 hours. The asymmetric location of the region of high median intensities with respect to the midnight meridian is perhaps related to longitudinal drift since, according to most magnetospheric electric field models, there is a net eastward drift expected for trapped ions with energies of a few keV or less in the dawn section in this L range [Kavanagh et al., 1968; McIlwain, 1974]. If one looks at this hypothesis more quantitatively, however, one finds that the observed delay times are probably too short to be explained by a longitudinal drift of the $O^+$ ions from the local time sector of high-median peak intensities (21-09 hours). Consider first the December 17 storm for which the more definitive early-time dayside data were obtained. The time delay between the initial increases observed on the night and daysides is $\approx 1.4$ hours. Depending upon the details of the magnetospheric electric field model and the specific particle energy, ions in the few-keV range injected in the midnight sector can longitudinally drift either eastward or westward. The shortest delay time expected for eastward drifting ions would be for those of 0 energy and this would be about five to ten hours for drift from 0900 to the observation point at 1500 LT [Kavanagh et al., 1968; McIlwain, 1974]. The shortest delay expected for westward drifting ions would be for the most energetic particles. Assuming E = 7.8 keV (the average energy of the initially observed dayside group) and L = 3.8 (the position of the median integral energy flux for this group) and neglecting convection for a lower limit we find that about nine hours would be required to drift from 2100 to 1500 LT for ions mirroring at low altitudes. For equatorially trapped ions, the corresponding time is about 6.5 hours. For the December 16 storm, there are possible ambiguities because of the low flux intensities and data gaps, but the time delay between the initial increase on the night and daysides is most probably $\approx$ 3.2 hours. A similar drift calculation to that described above shows that a delay time of greater than 6.3 hours would be required for ions mirroring at low altitudes and 4.4 hours for equatorially mirroring ions. We conclude that the initially observed $O^+$ ions in both storms are not likely to be convected around from the nightside but more probably are accelerated locally. The observed delay times can perhaps be understood in terms of the time required for the energetic ring-current protons (a proposed energy source for the $O^+$ acceleration [Cladis, 1973a,b]) to drift around westward from the nightside sector. For example, equatorially-trapped 50-keV protons would drift from midnight to 1500 LT at L = 6 in about one hour.

If the initially observed $O^+$ ions on the dayside are indeed accelerated locally, this provides a significant constraint on models of the acceleration mechanism. It must be one that operates effectively under widely different ionospheric conditions to accelerate particles from both the day and nightside ionospheres.

Although the initially observed $O^+$ ions have apparently not convected from the nightside, those observed later in the storm might have done so. The observed softening in the average energy of the dayside $O^+$ ions about five hours after the initially observed nightside increase in the December 17 storm is in about the right period for the expected time of arrival of eastward convecting soft ions.

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We have remarked on the general correspondence between the $O^+$ intensity parameters and the geomagnetic disturbance indices. To examine this relationship in more detail we have superimposed plots of the Dst and AE indices and the nightside $O^+$ intensity parameter on the same logarithmic scale in Figures 6 and 7. For the Dst plot (Figure 6) we have inverted the ordinate so that increasing ring current intensity corresponds to increasing $O^+$ intensity. One sees that there is indeed a significant correlation between the various quantities throughout the period of the study indicating that the energized $O^+$ results from a strong coupling between the ionospheric source and the magnetosphere. The correlation with Dst is suggestive of a ring-current energy source as has been suggested by Cladis [1973a,b] and Brice and Lucas [1975], or alternatively that the $O^+$ ions contribute substantially to the ring current. On the other hand the correlation with AE suggests the possibility of a source associated with magnetospheric substorms, for example through the acceleration of the ionospheric ions by the field aligned electric fields expected to result from the anomalous resistivity caused by the enhanced Birkeland currents associated with substorms [Thorne, 1975]. $O^+$ ions have been reported during substorms by Johnson et al. [1975].

If the $O^+$ source mechanism were indeed proportional to the ring-current intensity (Dst) or the strength of electrojet activity (AE) and the $O^+$ ions were directly precipitated with negligible trapping lifetime, we would expect a detailed correspondence between the precipitated $O^+$ intensity and the appropriate geomagnetic index. We see in Figure 6 that the ring-current hypothesis fits reasonably well to the early-time data in both storms. The apparently shorter decay time for the $O^+$ intensity than for Dst and the large increase in $O^+$ intensity near 1500 UT on December 18 which is not reflected in Dst argues against this model for the later phases of the storm.

The substorm hypothesis relevant to Figure 7 also gives a rough qualitative fit to the observations. In particular, we note the corresponding peaks in the two parameters around midday on the 18th. We would, however, hesitate to conclude that the correlation with AE shown in Figure 7 is definitely superior to that with Dst in Figure 6 on the basis of this limited amount of data.

A model utilizing a ring-current energy source that would allow for different decay times for the observed $O^+$ intensity and the Dst index is one in which the observed $O^+$ is precipitating from a trapped parent population which is controlled by decay processes different from those for the energetic protons which presumably are primarily responsible for the ring current, at least at later times in the storm [Berko et al., 1975].

The best estimate of the $O^+$ decay time to use for these considerations is probably obtained from the data in the 0000-0600 UT time period on December 18 when both AE and Dst are declining nearly monotonically and injection processes are presumably weak. We find that in this period the nightside $O^+$ precipitation is falling off with about a 2-1/2 hour time constant. This is substantially shorter than the estimated decay time resulting from strong pitch-angle diffusion or charge exchange for a longitudinally uniform trapped population of $O^+$ ions. For the nightside $O^+$ data, the invariant latitude of the median integral energy flux varies from $64^\circ$ to $70^\circ$ during this period and the average $O^+$ energy is about 4.5 keV. The minimum lifetime for strong pitch-angle diffusion corresponding to these values for $O^+$ ions varies over the range from approximately 17 to 78 hours [Kennel, 1969]. The appropriate charge exchange lifetime for equatorially mirroring $O^+$ ions is greater than four days based on the lifetimes for proton charge exchange given by Swisher and Frank [1968] modified by the ratio of the charge exchange cross sections for $H^+$ on H and $O^+$ on H summarized in Fite et al. [1962].

Let us consider two simple trapping models that attempt to explain both the observed $O^+$ decay time and the asymmetry in the local time distribution of peak $O^+$ intensities reported by Shelley et al. [1974], assuming a symmetric injection region around midnight. For the first model we assume that the $O^+$ ions are trapped but precipitating under strong pitch-angle diffusion so that the time dependence of the $O^+$ intensity parameter also represents the time dependence of the trapped flux intensity at 0300 LT. Consider the decay of a longitudinally limited cloud of ions injected into the 2100-0300 LT sector. The lifetime of the population at 0300 LT is determined by both precipitation and the depletion of the trapped population by longitudinal drift and convection. A detailed convection calculation is beyond the scope of this work but we can get some idea of the time scales involved by considering the motion of zero energy ions using current magnetospheric electric field models [McIlwain, 1972, 1974]. A cloud of such ions with the local time extent assumed above would take of the order of an hour to convect past the observation point at 0300 LT. More energetic ions would take longer because their gradient and curvature drifts oppose the convection motion. Depending on the details of the assumed electric fields, ion energies, and pitch-angle distributions and including the effect of precipitation, the model could probably be fit to the observed $O^+$ decay time.

The decrease in the local time distribution of peak flux intensities at $\approx$ 0900 LT reported by Shelley et al. [1974] might be interpreted in this model as resulting from the decay of the trapped population through precipitation in the time it takes to convect from the injection region to 0900 LT. For this to occur the convection time would have to be comparable to the precipitation lifetimes and this seems somewhat long, but not clearly excluded. Some local acceleration on the dayside would still be required in this model to explain, for example, the small time delay observed between the rise of the dayside and nightside $O^+$ fluxes shown in Figure 2.

For our second model, let us assume again that the observed $O^+$ ions are precipitating from a parent trapped population but that the precipitation is not necessarily proportional to the trapped flux intensity. We can assume, for example, that during the recovery phase the strength of pitch-angle diffusion declines and the observed 2-1/2 hour time constant is not representative of the decay of the trapped flux intensity but of the precipitation mechanism. The extent toward morning of the local time asymmetry would then be determined by how far the $O^+$ ions convect in the time period when the precipitation mechanism is most effective. In the storms described here, the time from the initial $O^+$ increase until the flux begins to fall off more rapidly than Dst is about 10 to 12 hours. Again, this is getting into the range where a fit to a convection calculation appears possible depending on the details of the model.

The correlations between the properties of the protons and the $O^+$ ions apparent in Figures 3 to 5 apply additional constraints to these phenomenological models. The tracking of the location of the two precipitation zones could arise from common motions of trapped populations of the two species; from a process in which the $O^+$ ions were energized by a mechanism involving the

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trapped protons as an energy source; or from a process in which the protons and $O^+$ ions were accelerated together from the ionosphere by the same mechanism. In the latter two cases a substantial trapped $O^+$ population would not necessarily be involved. The correlations in the variations in average energies of the two species on the dayside seem most directly interpretable in terms of storm-associated acceleration processes acting upon the parent trapped populations, or in terms of a common ionospheric source for the two ion species and a common acceleration mechanism varying in efficiency during the storm-time period. This latter interpretation would have far-reaching effects on the present state of thinking about the origin of the energetic magnetospheric proton population [Hill, 1974].

We have briefly explored a few of the constraints which these morphological results can exert on possible source and energization mechanisms for the $O^+$ ions. It is hoped that more quantitative models will be investigated by others utilizing the experimental results presented here and in Paper II.

As discussed in the "Analysis and Results" section, the zone integral intensity values can be considered as an approximation to the energy flux precipitating into a one-cm-wide strip transverse to the precipitation zone. If we knew the local time distribution of the fluxes, we could estimate the instantaneous worldwide precipitated ion flux in this energy range during the course of the storm. The local time distribution of precipitating protons can be estimated from the $H_\beta$ observations of Eather and Mende [1971] and Mende (private communication). A rough estimate for the local time distribution of the $O^+$ ions can be obtained from the work of Shelley et al. [1974]. From these results we find that a reasonable approximation to the local time average of the flux intensity can be formulated from the average of our measured values at 1500 and 0300 hours local time. By assuming conjugacy and isotropic pitch-angle distributions over the upper hemisphere, we can approximate P, the total worldwide precipitated energy flux in the range ($0.7 \leq E \leq 12$ keV) as

$$P \approx 2\pi^2 R_E \left(F_N \cos \Lambda_N + F_D \cos \Lambda_D\right) \text{ ergs/sec}$$

where F = the zone integral energy flux (Figure 2), $\Lambda$ = the invariant latitude of the 50% point of the zone integral (Figure 5), and the subscripts D and N refer to day (1500 LT) and night (0300 LT), respectively. Plots of P for both the $H^+$ and $O^+$ ions are given in Figure 8.

If we assume that the precipitating ion fluxes originate from (or derive their energy from) the trapped population responsible for the stormtime ring current we can ask what fraction of the ring-current energy is lost through ion precipitation. The instantaneous value of Dst can be related to the total energy content of the trapped ring-current particles ($E_R$) by the expression $Dst(\gamma) = 2.6 \times 10^{-21} E_R$, where $E_R$ is given in ergs [Sckopke, 1966; Frank, 1967].

In order to have directly comparable quantities we would like to make the comparison between P and changes in Dst in a time period when ring-current injection processes are negligible. Davis and Parthasarathy [1967] have shown that during such periods AE is relatively low and Dst decays exponentially with a time constant of about ten hours. The time period from 0000 to 0800 UT on December 18 fulfills these conditions. During this period $\Delta E_R = 2.8 \times 10^{22}$ ergs are lost from the ring current according to the above relationship. By integrating the curves in Figure 8 over this interval, we find that the worldwide energy loss from precipitating ions with energy between 0.7 and 12 keV is $\Delta E_O = 6 \times 10^{20}$ ergs of $O^+$ ions and $\Delta E_P = 8 \times 10^{20}$ ergs of protons, together accounting for about 5% of the lost ring-current energy.

The major portion of the ring current energy is carried by protons with energies above the range of our spectrometers. If we characterize the entire ring current by the proton spectrum measured by Explorer 45 during this same time period at the latitude of the maximum of the equatorial energy density (L = 3.6), we can roughly estimate $\epsilon$, the fraction of the ring-current energy density carried by ions with $E < 12$ keV. Integrating the orbit 102 spectrum in Figure 3 of <u>Smith and Hoffman</u> [1973] we find that $\epsilon \approx 9\%$ of the energy is in these low-energy ions. Thus $f = (\Delta E_O + \Delta E_P)/\epsilon E_R \approx 60\%$ of the ring-current energy loss in the energy range of these measurements can be accounted for by precipitation.

The Explorer 45 energy spectrum which we have utilized was constructed with data from two types of instruments. The lower energy portion ($E < 30$ keV) was measured with an electrostatic analyzer which would have counted any $O^+$ ions in the equatorial plane. The upper energy portion was measured with solid-state detectors which are relatively insensitive to $O^+$ ions because of the increased losses of the heavier ions in the dead layer of the detector. By utilizing the spectrum as published we have essentially assumed that the equatorially trapped $O^+$ fluxes are negligible during this period. An alternative assumption is that the $O^+$ fluxes have a similar equatorial pitch-angle distribution to that of the protons. In this case we would modify the published spectrum at the low energies by deleting the $O^+$ contribution according to the $H^+/O^+$ ratio measured at low altitudes during this period. Under this assumption only 6% of the trapped proton energy density is carried by protons with energies below 12 keV and $f \approx 80\%$ of the ring current energy loss in this energy range is accounted for by precipitating ions.

In order to estimate the fraction of the <u>total</u> ring current (ions of all energies) lost by precipitation we need a determination of the spectrum of the precipitating ions. These are expected to be generally softer than the trapped ions due to the energy loss experienced during pitch-angle diffusion. There are no data for the $O^+$ ions above 12 keV, but for a first order estimate, we assume an exponential spectrum with a characteristic energy $\approx$ 15 keV for both ion species based on satellite measurements of auroral protons [<u>Sharp et al.</u>, 1967]. The above expression for f is still applicable with $\epsilon$ now representing the fraction of the energy <u>flux</u> carried by ions with $E < 12$ keV. This yields an estmmate of $f \approx 25\%$ of the total ring current energy lost by precipitation during this period.

We conclude from these considerations that precipitation was a major loss mechanism for ring-current ions with energy less than 12 keV during this storm and may have been an important loss mechanism for the entire ring current. If a large fraction of the precipitating ions derive their energy from sources other than the ring current, these conclusions are of course not valid. One obvious such source is the magnetosheath which is known to contribute to the dayside proton precipitation at high latitudes [<u>Heikkila and Winningham</u>, 1971]. We do not feel that the polar cusp particles contribute substantially to the measured integrals however; since, as will be seen in Paper II, the average proton energies even at high latitudes on the dayside remain in the few-keV range, well above the average proton energy in the cusp. In any case, even deleting the dayside proton data completely would only reduce the above estimates by about 25%.

Our conclusions about the importance of ion precipitation as a loss mechanism in this storm are in disagreement with the conclusions of Mizera [1974] for the higher energy particles during the March 19-20, 1969 magnetic storm. The details of his calculation were not presented, but on the basis of electrostatic analyzer data he concluded that less than 1% of the ring-current energy lost during that storm could be attributed to precipitating protons with $E > 12$ keV.

## SUMMARY AND CONCLUSIONS

Some of the principal results of this study of the zone integral parameters of the precipitating $O^+$ and $H^+$ ions during the December 16-18, 1971 storm period are:

1) The intensity of the precipitating $O^+$ ions was found to be well correlated with the geomagnetic indices which measure the strength of magnetospheric substorm activity and the strength of the storm-time ring current. Since the $O^+$ ions are almost certainly of ionospheric origin, these correlations indicate that a previously unknown strong coupling mechanism existed between the magnetosphere and the ionosphere during the period of the study.

2) The storm-associated initial increase of the $O^+$ ions on the nightside (0300 LT) was found to lead that on the dayside (1500 LT) and

lag the initial nightside $H^+$ increase by more than one hour in both storms. A consideration of ionic transport processes leads to the conclusion that the mechanism accelerating the $O^+$ ions is probably operative in the dayside as well as the nightside ionosphere. This is significant in that it implies that this unknown mechanism can be operative over a wide range of ionospheric and magnetospheric conditions.

3) Correlations have been found between the locations of the $O^+$ and $H^+$ precipitation zones and between the average energies of the two ionic species. From these and other morphological features, it is inferred that the $O^+$ ions are probably either accelerated together with the protons or coexist with them as a trapped population for an extended period. Either of these hypotheses imply that the ionospheric contribution to the storm-time ring current may be more significant than has previously been considered.

4) The total worldwide precipitated ion energy flux has been estimated during the period of the study and compared to the ring-current energy content as measured by Dst. The comparison indicates that precipitation was an important loss mechanism for ring-current ions with energies less than 12 keV during the December 17-18, 1971 magnetic storm.

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We would like to thank D. L. Carr for his assistance with the data reduction and analysis. The satellite experiment was supported by the Defense Nuclear Agency through the Office of Naval Research. This anal-

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ysis has been supported by the Air Force Office of Scientific Research under Contract F44620-73-C-0050, by NASA under Contract NASw 2777, and by the Lockheed Independent Research program.

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# FIGURE CAPTIONS

Fig. 1. Geomagnetic disturbance indices for the period under study.

Fig. 2. Zone integral intensity parameters for precipitating ions with energies $0.7 \leq E \leq 12$ keV.

Fig. 3. Average energies of the precipitating ions in the energy range of the experiment.

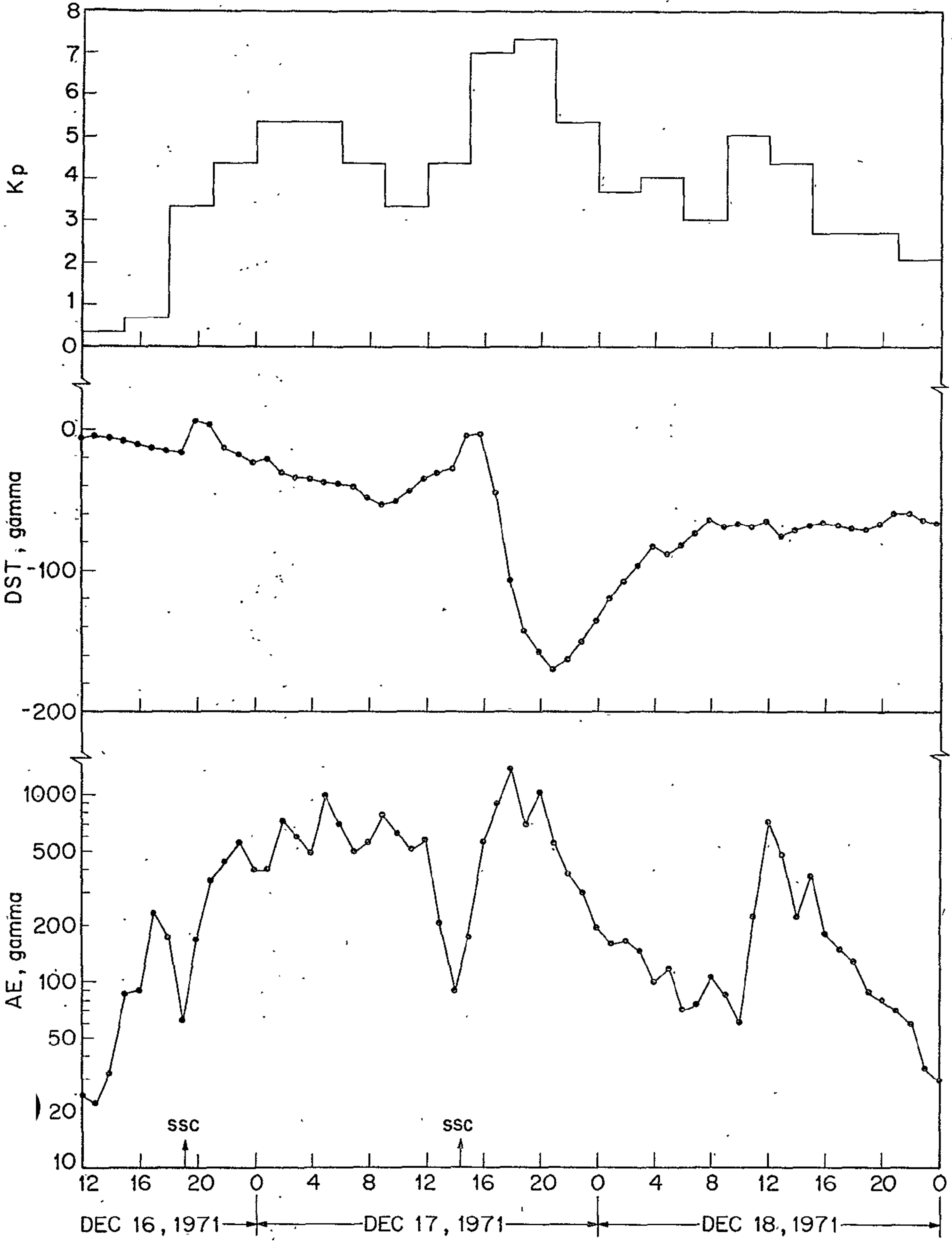
Fig. 4. Alternative definition of average ion energy (see text for details).

Fig. 5. Locations of the zones of precipitation for the $O^+$ and $H^+$ ions.

Fig. 6. Nightside $O^+$ intensity parameter compared with Dst.

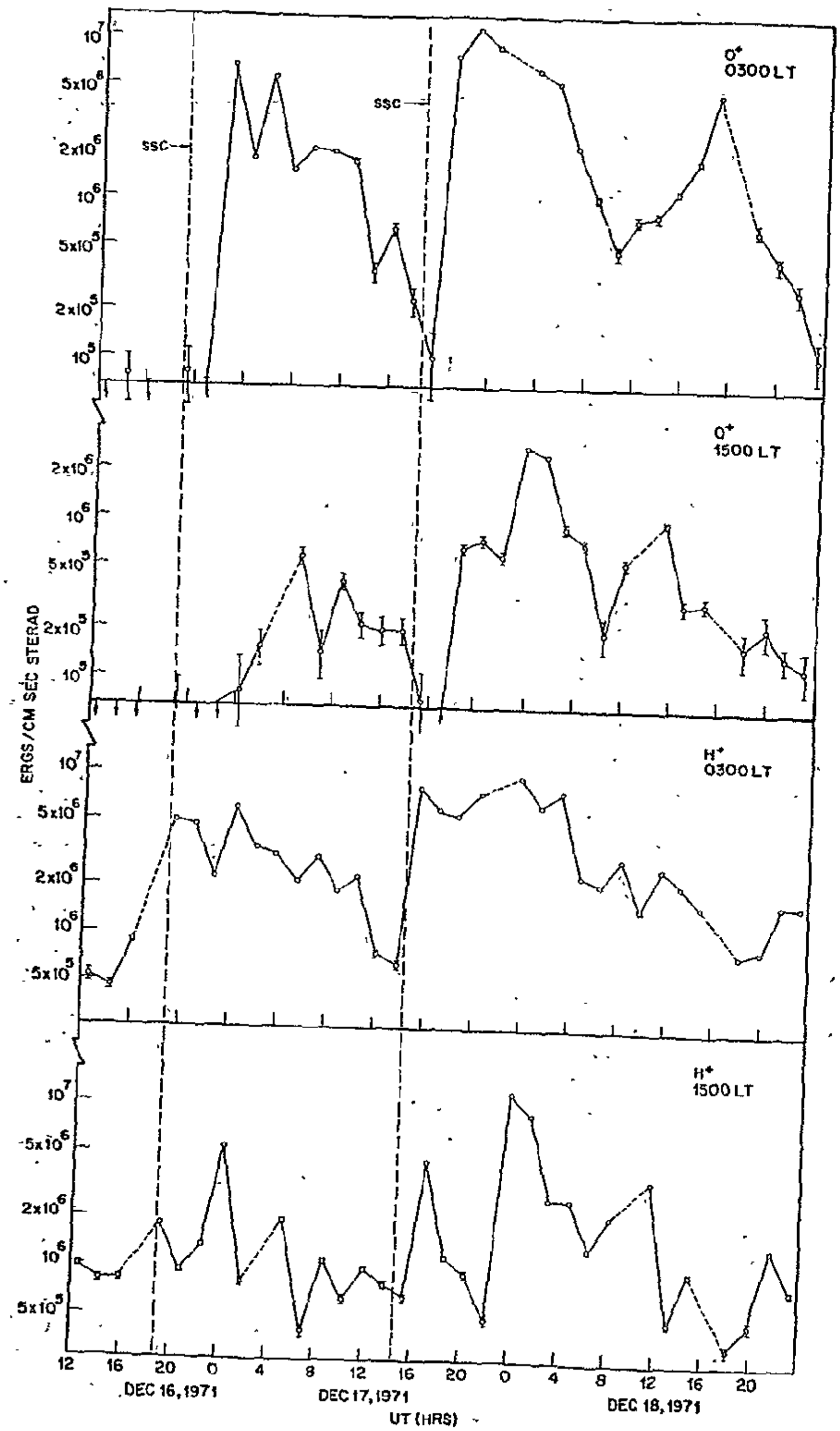
Fig. 7. Nightside $O^+$ intensity parameter compared with AE.

Fig. 8. Total worldwide precipitated energy flux of $H^+$ and $O^+$ ions in the energy range of the experiment. The asterisks indicate lower limits determined from the nightside observations alone at times when the dayside measurements were not available.



Kp
DST, gamma
AE, gamma
SSC
SSC
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971


FIGURE 1



O+
0300 LT
SSC
O+
1500 LT
H+
0300 LT
H+
1500 LT
ERGS/CM SEC STERAD
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971
UT (HRS)


FIGURE 2

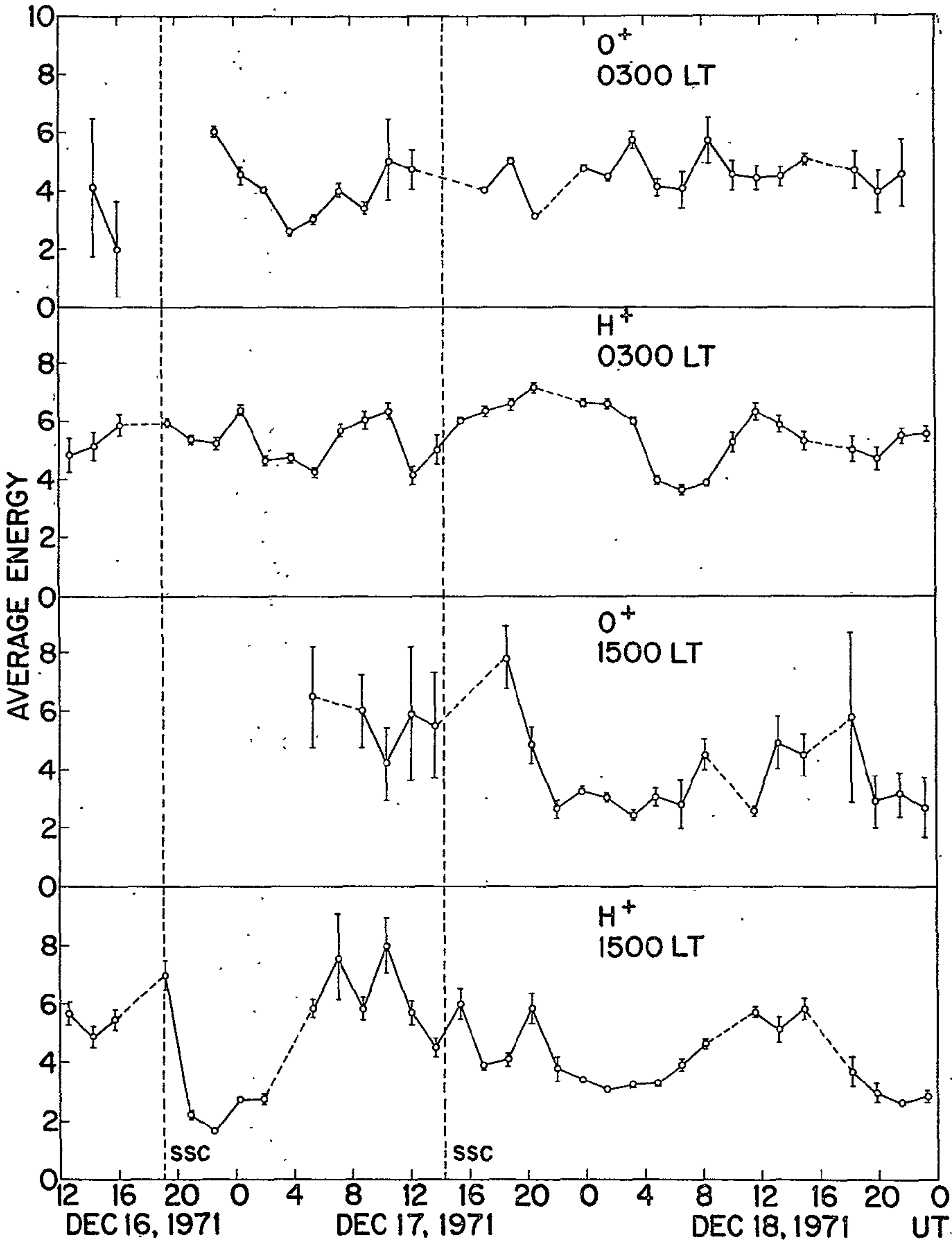

O+
0300 LT
H+
0300 LT
O+
1500 LT
H+
1500 LT
AVERAGE ENERGY
SSC
SSC
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971
UT

FIGURE 3

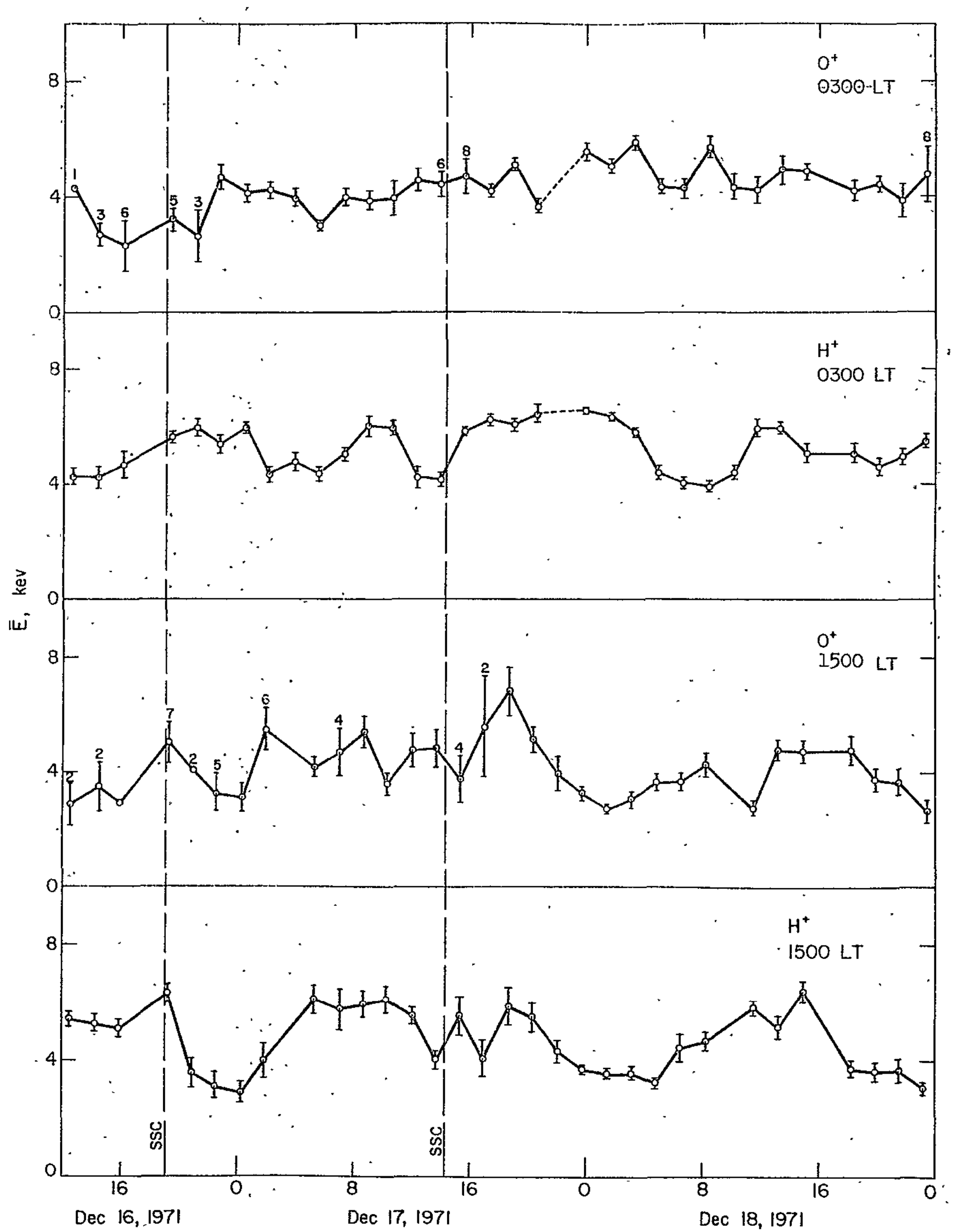
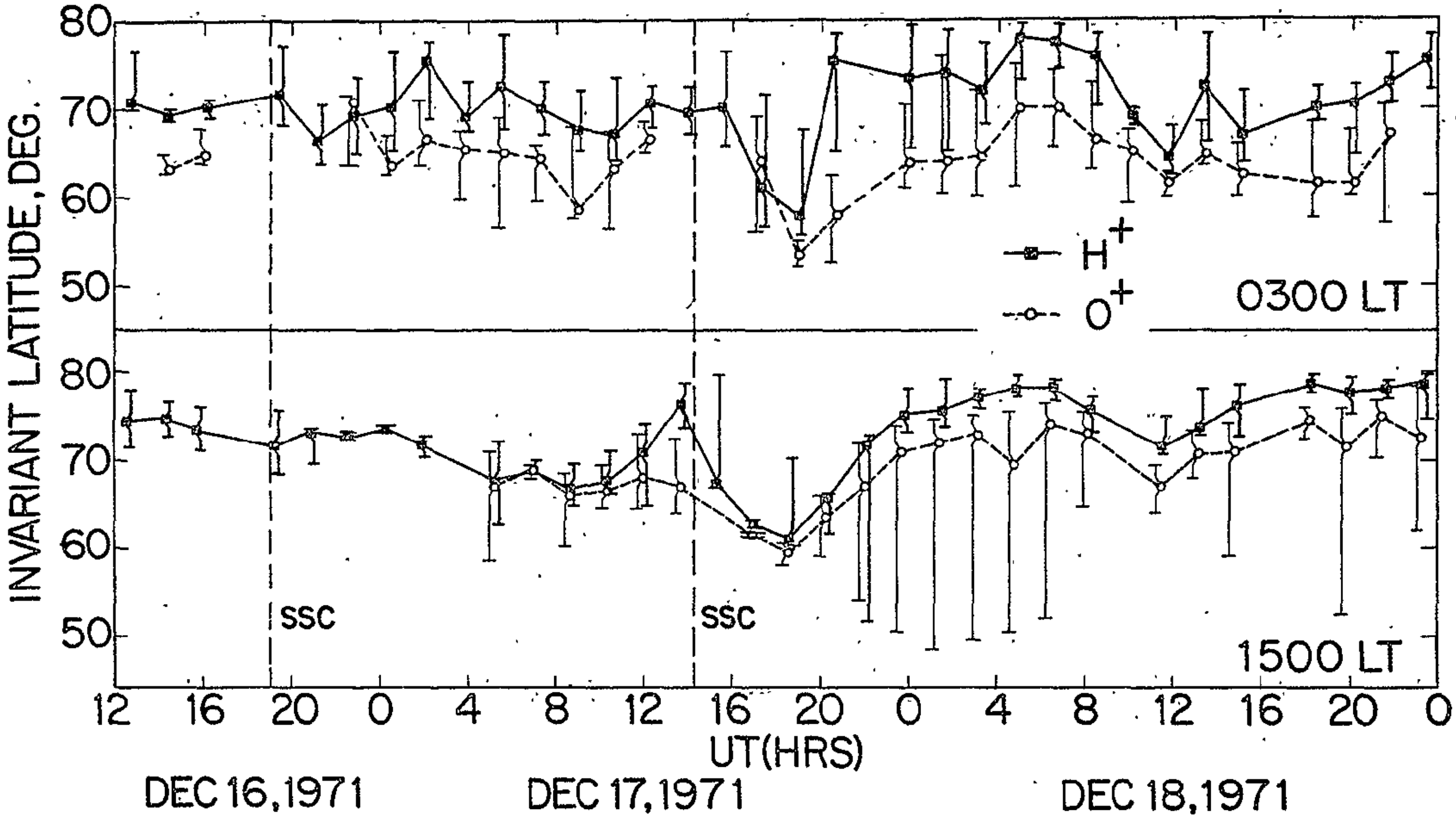
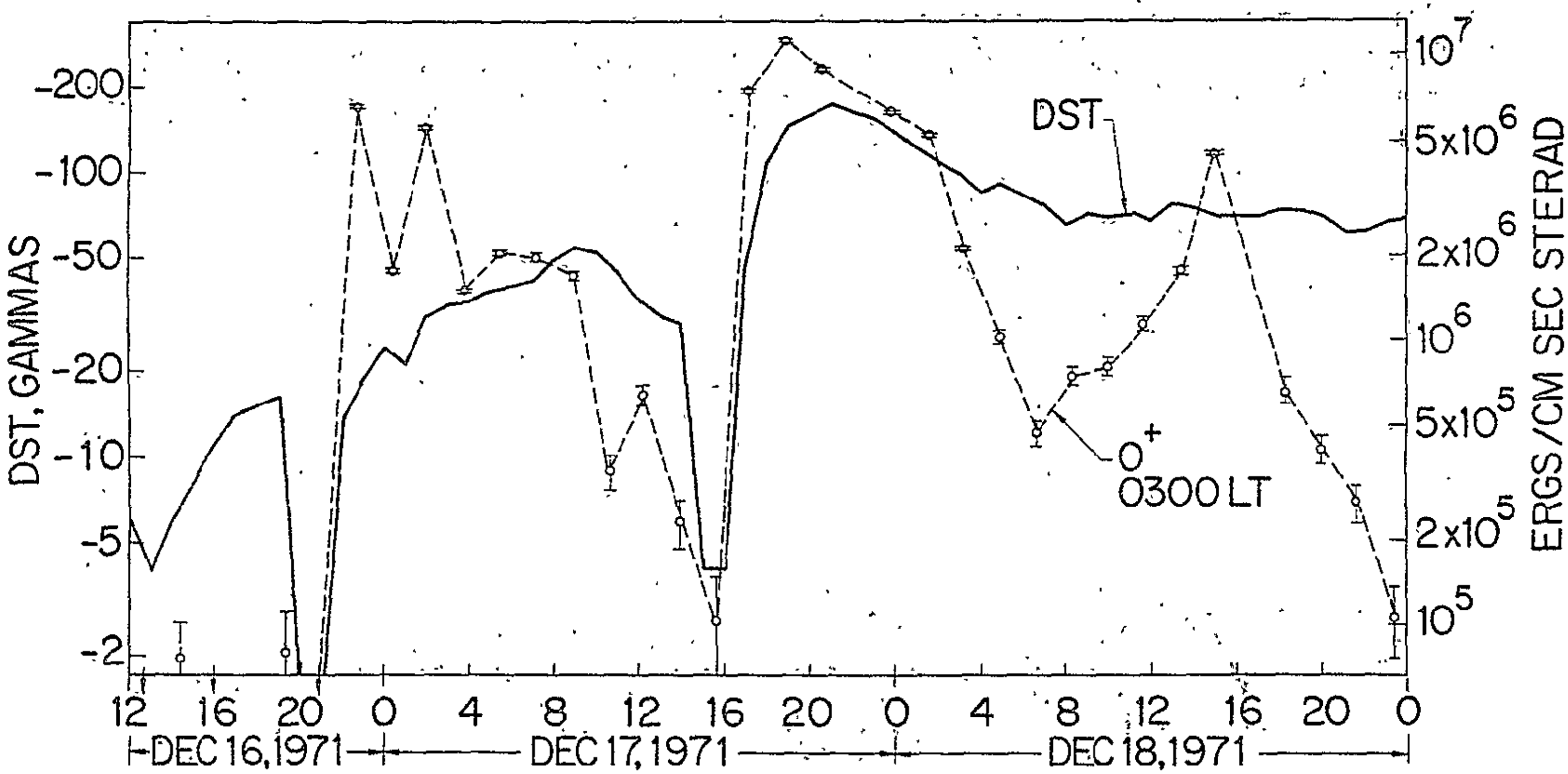

O+
0300 LT
H+
0300 LT
O+
1500 LT
H+
1500 LT
Ē, kev
SSC
SSC
Dec 16, 1971
Dec 17, 1971
Dec 18, 1971

FIGURE 4



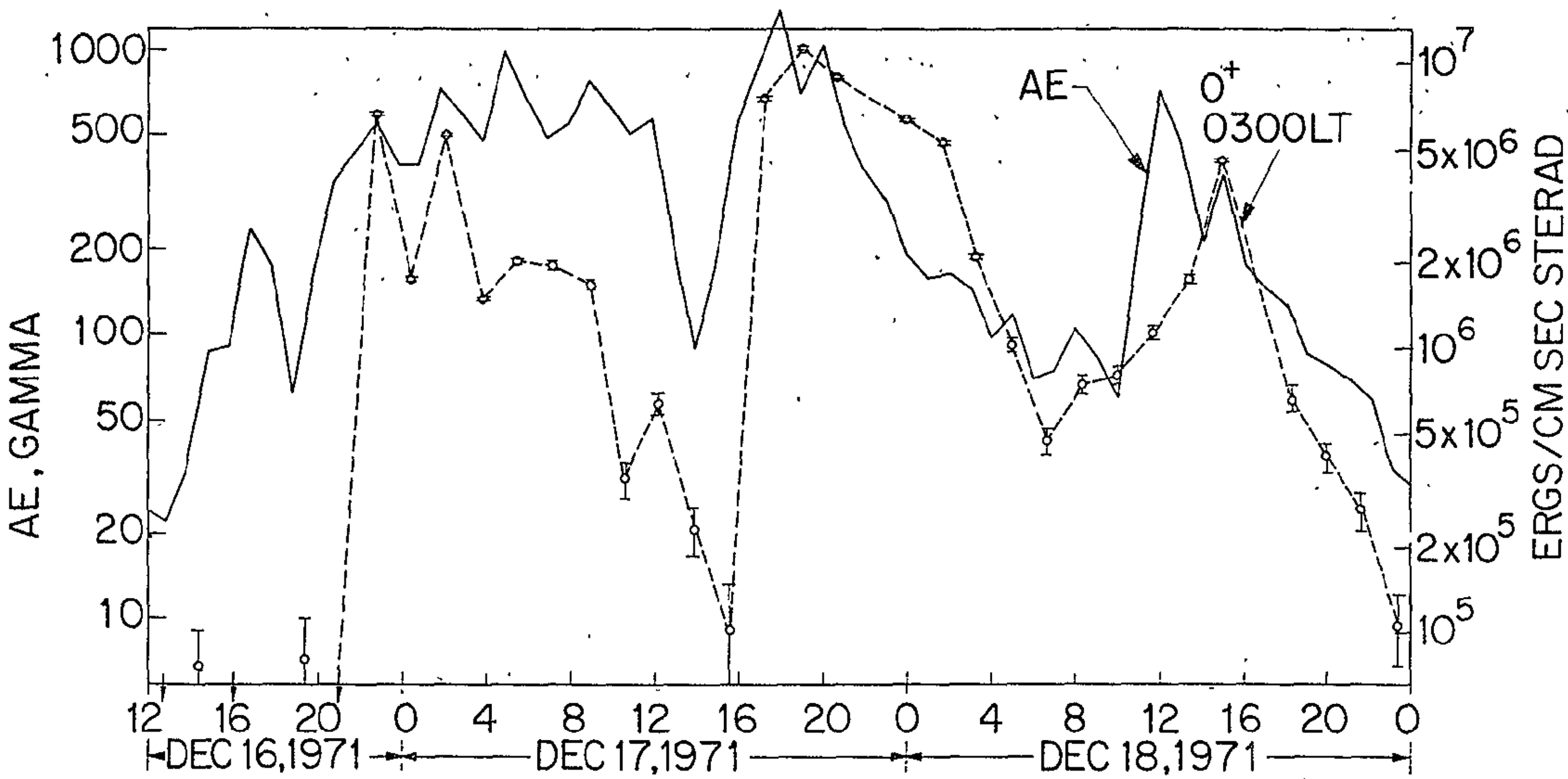
80
70
60
50
INVARIANT LATITUDE, DEG.
H+
O+
0300 LT
SSC
SSC
1500 LT
12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0
UT(HRS)
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971


FIGURE 5



DST, GAMMAS
-200
-100
-50
-20
-10
-5
-2
DST
$O^+$
0300 LT
$10^7$
$5x10^6$
$2x10^6$
$10^6$
$5x10^5$
$2x10^5$
$10^5$
ERGS/CM SEC STERAD
12
16
20
0
4
8
12
16
20
0
4
8
12
16
20
0
DEC 16,1971
DEC 17,1971
DEC 18,1971


FIGURE 6



1000
500
200
100
50
20
10
AE, GAMMA
$10^7$
$5x10^6$
$2x10^6$
$10^6$
$5x10^5$
$2x10^5$
$10^5$
ERGS/CM SEC STERAD
AE
$0^+$
0300LT
12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0
DEC 16,1971
DEC 17,1971
DEC 18,1971


FIGURE 7

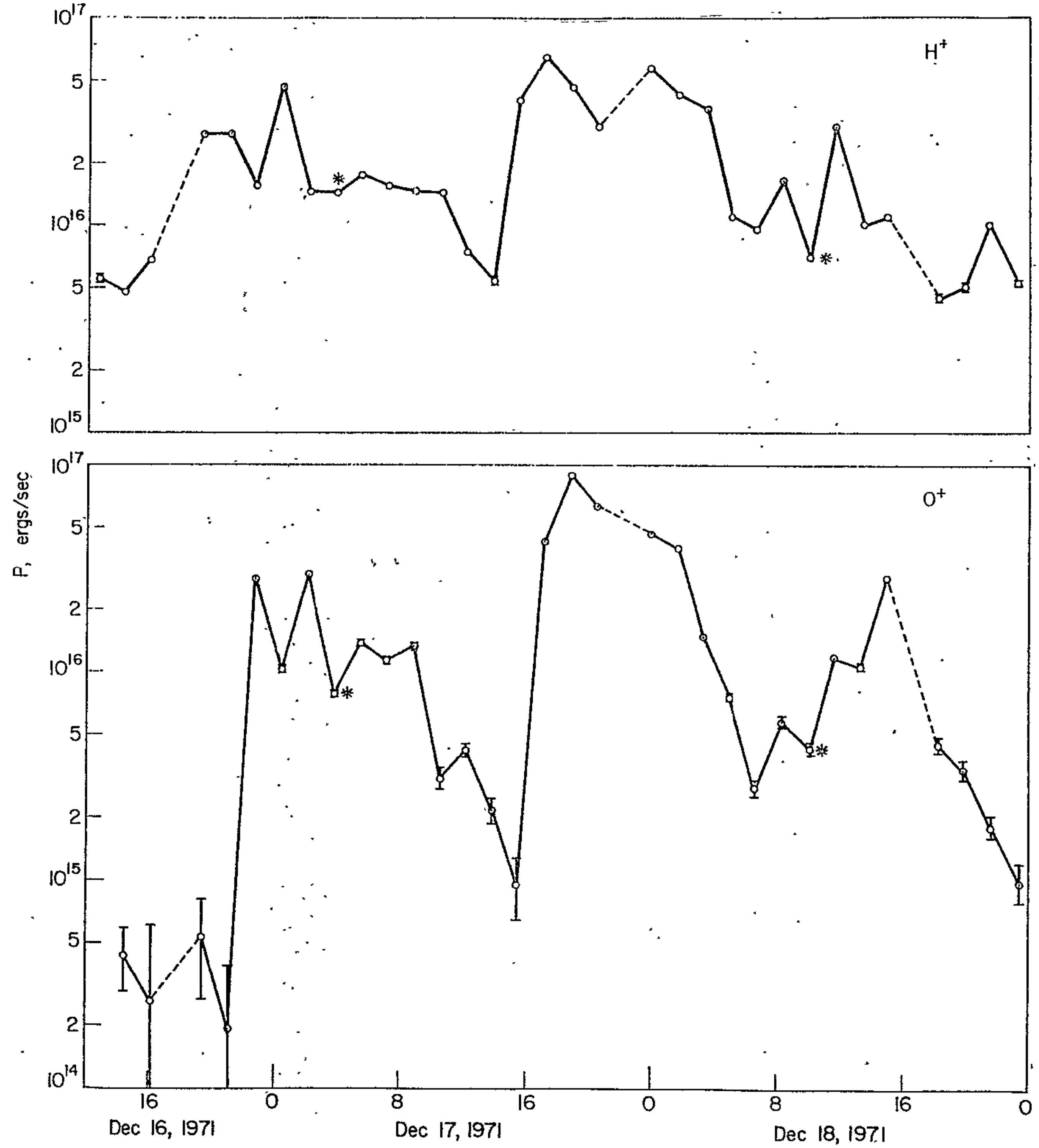



FIGURE 8

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APPENDIX B

# THE MORPHOLOGY OF ENERGETIC $O^+$ IONS DURING TWO MAGNETIC STORMS: LATITUDINAL VARIATIONS

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# THE MORPHOLOGY OF ENERGETIC $O^+$ IONS DURING TWO MAGNETIC STORMS: LATITUDINAL VARIATIONS

R. D. Sharp, R. G. Johnson and E. G. Shelley

ABSTRACT

This is the second of two papers describing the results of a study of precipitating $O^+$ and $H^+$ ions with energies between 0.7 and 12 keV during the magnetic storms of December 16 and 17, 1971. This paper emphasizes the latitudinal variations of the properties of the precipitating ions and discusses some characteristics of the $O^+$ energy spectrums. Some of the principal findings are: the $O^+$ energy spectrums were generally quite structured with one or more peaks being frequently observed; $O^+$ energy spectrums which were still rising at 12 keV were not uncommon, particularly at high latitudes; several examples of a spectral peak moving systematically to higher energy with increasing latitude were found; a significant hardening of the $O^+$ spectrum with increasing latitude was observed during the December 17 storm as well as a significant hardening with decreasing latitude at the low-latitude edge of the precipitation region on the nightside; precipitating $O^+$ ions at $L \leq 2$ were found in association with a large main phase decrease in Dst; a small but statistically significant difference in average energies between protons and $O^+$ ions in the range 0.7 to 12 keV was observed with the protons being somewhat harder.

## INTRODUCTION

The existence of a previously unknown mechanism responsible for the acceleration of cold ionospheric plasma up to energies of 12 keV was established by Shelley et al. [1972] with the discovery of large fluxes of energetic $O^+$ ions in the magnetosphere. In order to search for clues to the nature of this mechanism, a detailed study was undertaken of the properties of the $O^+$ and the accompanying $H^+$ ions during the December 16-18, 1971 period which included two principal magnetic storms. It is recognized, of course, that if the observed ions were being precipitated from a trapped population, the observed characteristics might also reflect ion transport and loss processes which have occurred.

This is the second of two papers describing the results of the study. Paper I [Sharp et al., 1975] discussed the temporal variations of parameters characterizing the intensity, spectral hardness, and location of the zones of precipitation of the ions. This paper will emphasize the latitudinal variations in these parameters and will also describe some typical characteristics of the $O^+$ energy spectrums and give the results of an intercomparison of the $O^+$ and $H^+$ average energies during each storm.

## ANALYSIS AND RESULTS

As a first step in a search for systematic latitudinal effects in the $O^+$ data, plots of the spectrums and average ion energies as a function of latitude were examined for selected individual passes on the northern hemisphere day ($\approx$ 1500 LT) and night ($\approx$ 0300 LT) crossings of the precipitation region. Particular attention was given to the passes showing the initial $O^+$ flux increase in each storm (the "initial increase passes") with the hope that these passes might exhibit some signature of the source before drift effects in a possible trapped population could obscure the systematics.

In both storms, the $O^+$ data from the initial increase passes on the nightside (Revolution 864 at 2246 UT on December 16 and Revolution 875 at 1714 UT on December 17--see Figure 2 of Paper I) consisted principally of structured spectrums which contained one or more peaks. On Revolution 864 the nightside data at the highest latitude where there was significant flux intensity showed a spectrum which was still rising at the highest energy channel of the spectrometer implying that the spectral peak was above 12 keV. This spectrum is shown in Figure 1. It is a 61.4-second average of the data from ten instrument cycles taken over the invariant latitude range from about 70° to 73°.

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In the December 17 storm the initial increase pass showed peaked energy spectrums over a wide latitudinal range with the peak systematically moving to higher energies with increasing latitude. Spectrums formed from the 61.4-second (10-cycle) averages of the data on this pass are shown in Figure 2 for those times where the flux was sufficiently intense that the spectrums were statistically significant.

Two-degree latitudinal averages of the average $O^+$ energy in the range $0.7 \leq E \leq 12$ keV for both these passes are shown in Figure 3. The average energy was defined as the ratio of the integral energy flux averaged over the two-degree interval to the integral number flux averaged over the same interval. The average energy was considered significant only for those two-degree intervals where the average integral number flux was greater than twice its standard deviation as determined from the counting statistics. The average energies for those intervals where the flux intensity was weaker than this significance threshold have been deleted. One sees in Figure 3 that on both these passes the $O^+$ ions showed a significant hardening at both the high and low latitude ends of the region of principal precipitation. On Revolution 875 where there was a more latitudinally extended precipitation region, a spectral hardening with increasing latitude occurred over most of that region, as was also indicated by the data shown in Figure 2. An alternative definition of the average energy which will be discussed below gave essentially the same results as those illustrated in Figure 3.

In both storms, the initial increase passes on the dayside (at 0159 UT on December 17 and 1837 UT on December 17) also contained examples of spectrums which were still rising at 12 keV. There were no obvious systematic latitudinal effects in these dayside passes, but the fluxes were too weak or occurred over too narrow a latitudinal interval to be able to make a definitive determination of the existence of such effects.

The examination of the 61.4-second spectral averages from other selected passes in both storms showed that the spectrums were generally quite structured in the range of the measurements with one or more peaks typically being observed. Spectrums with a peak at 12 keV or higher, similar to the one shown in Figure 1 were not uncommon, particularly at high latitudes. On the nightside, several examples were found similar to Figure 2 with the spectral peak moving to higher energy with increasing latitude.

In the December 17 storm on both the day and night sides, plots of the average $O^+$ energy for the individual passes showed a systematic hardening at high latitudes which was readily apparent in most of the passes where the flux was sufficiently intense over a wide enough interval that a trend could be discerned. Some additional examples of nightside $O^+$ spectrums in this period were presented in Figure 7 of Shelley et al. [1972]. On the basis of the present more extensive analysis we can now state that the trend exhibited by those spectrums was indeed typical of the December 17 storm.

In the December 16 storm there were no systematic latitudinal effects obvious in the $O^+$ spectral data from the individual passes. The fluxes were typically too weak, however, to be able to make a definitive determination of the existence of such effects.

In order to search for systematic latitudinal effects with increased statistical precision, all of the data were averaged in two-degree intervals of invariant latitude over the range $44^\circ \le \Lambda_I \le 80^\circ$ for both storms. Averages of the integral energy flux, the integral number flux, and the average ion energy were computed for both protons and $O^+$ ions for all the day and nightside passes over the northern hemisphere precipitation zone during which data were acquired.

As discussed in Paper I, two alternative definitions of the average energy were used in order to insure that any observed trends were not the result of a specific weighting technique. The average energy as defined above in connection with Figure 3 is referred to as E*. This definition tends to weight most heavily the intense precipitation regions within each $2^o$ interval. An alternative quantity $\bar{E}$ was formed from the average of all the significant individual six-second spectrums within the two-degree interval, with each spectrum being weighted equally. The significance criterion on the individual spectrum was that the integral number flux had to be greater than twice its standard deviation as determined from the counting statistics. In plots of $\bar{E}$ the error bars represent the standard deviations of the means of the individual six-second average energies while in plots of E* the error bars represent the standard deviation determined from the counting statistics.

Plots of the grand averages of the two-degree latitudinal averages of the various quantities for the period of each of the two storms are shown in Figures 4 through 6. The December 16 storm averages contain data from 1912 UT on December 16 to 1354 UT on December 17. The December 17 storm averages contain data from 1521 UT on December 17 to 2326 UT on December 18 (see Figure 2 of Paper I).

The plots of the latitudinal dependence of the integral energy flux presented in Figure 4 show that the $O^+$ precipitation region is displaced equatorward from the $H^+$ region on the day and nightsides during both storms. On the nightside the intensities of the two species are comparable while on the dayside the $H^+$ intensity is dominant. It is of interest to note that there were substantial latitudinal intervals during both storms where the precipitating ion flux in the energy range of the measurements was almost entirely $O^+$.

The average energy results are shown in Figures 5 and 6. The numbers above the $\overline{E}$ points indicate the number of individual six-second average energies contained in the two-degree interval. Examining first the results for the $O^+$ ions, one sees that for the December 17 storm, there was a clearly significant hardening with increasing latitude on both the day and nightsides except for the significant hardening with decreasing latitude on the nightside just at the low-latitude edge as was observed in the initial increase pass. For the December 16 storm the same trends are indicated by the nightside data but are not evident in the dayside results. The average energies of the protons do not show comparable systematic changes with invariant latitude. However, a general spectral softening of the protons is evident in the dayside data above about 68° and in the nightside data above about 75°. From satellite measurements of the proton (total ion) fluxes at 1 keV and 6 keV, Hultqvist [1974] has reported a spectral softening of protons with increasing latitude at all local times, except when the fluxes are field-aligned. A direct comparison with the present results is not possible since the latitudinal and local time variations reported by Hultqvist have thus far been presented only for selected satellite passes. No significant indication is seen of

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the softening of the proton spectrum at the low-latitude edge of the precipitation region on the nightside as was observed by Burch [1973] during the initial phase of the May 7, 1968 storm. Also, there is no significant indication at these lower energies of the dramatic hardening at low latitudes reported for the higher energy component of the proton precipitation on the nightside by Sharp and Johnson [1968], Burch [1973], and Mizera [1974].

In order to present a synoptic picture of the development of the two storms, contour plots of the integral energy flux intensity versus invariant latitude and universal time were constructed from the $2^{o}$ latitudinally averaged values. These contour plots are shown in Figures 7 through 10. Data gaps are indicated by hatched strips. In examining the $O^{+}$ contours, one sees that for the December 17 storm the precipitation was initiated over a wide latitudinal front and tended to persist longest at the high latitudes. In this storm, which had a large main phase Dst decrease (see Figure 1 in Paper I) there were substantial $O^{+}$ fluxes deep within the magnetosphere extending below L = 2, while in the December 16 storm which had only a small main phase, the $O^{+}$ fluxes were restricted to the high latitudes. A similar but less pronounced characteristic was exhibited by the nightside $H^{+}$. The $H^{+}$ fluxes in general seemed less strongly modulated by the various phases of the storm than did the $O^{+}$. They extended to high latitudes ($\Lambda_L \geqslant 80^{o}$) with substantial intensities. This was perhaps an unusual feature of this specific storm. Anger et al. [1974] reported abundant polar cap auroral activity for an extended period during and after this storm.

On the dayside, there were occasional indications of two proton "zones" as were reported by Sharp et al. [1967] and Frank and Ackerson [1972] during periods of low magnetic activity; however, during most of the period of this study the dayside proton precipitation was contained within a single zone as has been the case during other active periods [Sharp et al., 1969].

As discussed in Paper I, the initial $O^+$ increase on the nightside occurred prior to that on the dayside and was delayed from the initial $H^+$ increase in both storms. The latitudinal dependences of these leads and lags are shown explicitly on the contour plots.

We have seen in Figures 5 and 6 that the average energies of the two ion species in the range of these measurements were about equal. In order to determine if there was a statistically significant difference between them we averaged over latitude for each species to compute the overall average energy for each storm. These values are shown in Table I where the quantities and uncertainties and the time periods of the two storms have the same definitions as in Figures 5 and 6. An examiniation of Table I shows that there is indeed a significant difference between the two species with the $O^+$ having a lower average energy. During the December 17 storm the nightside averages for both $O^+$ and protons were significantly harder than those on the dayside. One should treat these results with caution since the averages were formed over only a limited portion of the distribution function ($0.7 \leq E \leq 12$ keV). As indicated by the data in Figure 1 for $O^+$ and as is known from other work for $H^+$ [Eather and Carovillano, 1971], a substantial fraction of the energy distribution of the precipitating auroral ions can be outside the range of this experiment.

## SUMMARY

The spectral characteristics and latitudinal variations of the properties of the precipitating ions in the energy range 0.7 to 12 keV have been investigated for two magnetic storms. Some of the principal findings are:

1. The $O^+$ energy spectrums were generally quite structured with one or more peaks being frequently observed.

2. $O^+$ energy spectrums which were still rising at 12 keV were not uncommon, particularly at high latitudes.

3. Several examples of a spectral peak moving systematically to higher energy with increasing latitude were found.

4. A significant hardening of the $O^+$ spectrum with increasing latitude was observed at the higher latitudes during the December 17 storm as well as a significant hardening with decreasing latitude at the low-latitude edge of the precipitation region on the nightside.

5. Precipitating $O^+$ ions at $L \leq 2$ were found in association with a large main phase decrease in Dst.

6. A small but statistically significant difference in average energies between protons and $O^+$ ions in the range 0.7 to 12 keV was observed with the protons being somewhat harder.

## ACKNOWLEDGMENTS

We would like to thank D. L. Carr for his assistance with the data reduction and analysis. The satellite experiment was supported by the Defense Nuclear Agency through the Office of Naval Research. This analysis has been supported by the Air Force Office of Scientific Research under Contract F44620-73-C-0050, by NASA under Contract NASw 2777, and by the Lockheed Independent Research program.

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Table I

OVERALL AVERAGE ENERGIES IN THE RANGE $0.7 \leq E \leq 12$ keV

| | Night | | Day | |
|---|---|---|---|---|
| | E* (keV) | $\bar{E}$ (keV) | E* (keV) | $\bar{E}$ (keV) |
| Dec. 16 Storm | | | | |
| $H^+$ | 5.40 ± 0.05 | 5.18 ± 0.08 | 3.35 ± 0.05 | 4.98 ± 0.15 |
| $O^+$ | 4.19 ± 0.07 | 3.95 ± 0.11 | 6.72 ± 1.4 | 4.41 ± 0.19 |
| Dec. 17 Storm | | | | |
| $H^+$ | 5.84 ± 0.04 | 5.59 ± 0.06 | 3.56 ± 0.03 | 4.38 ± 0.09 |
| $O^+$ | 4.31 ± 0.04 | 4.82 ± 0.08 | 3.23 ± 0.08 | 3.66 ± 0.10 |

FIGURE CAPTIONS

Fig. 1. Energy spectrum of $O^+$ ions averaged over a 61.4-second interval at 2245 UT on Dec. 16, 1971. The dotted line indicates a flux level corresponding to one standard deviation above zero. Points with values less than this level have been deleted.

Fig. 2. 61.4-second averages of the $O^+$ energy spectrums during the period 1712 to 1718 UT on Dec. 17, 1971.

Fig. 3. Average $O^+$ energy in $2^o$ latitudinal intervals during the satellite pass showing the initial $O^+$ flux increase in each storm. The upper figure shows data from 2244 to 2252 UT on Dec. 16, 1971. The lower figure shows data from 1713 to 1720 UT on Dec. 17, 1971.

Fig. 4. Precipitating energy flux at $\approx$ 0300 local time (nightside) and at $\approx$ 1500 local time (dayside) averaged in two-degree latitudinal intervals over each of the two storms. The plots onthe left contain data from 1912 UT on Dec. 16 to 1354 UT on Dec. 17. The plots on the right contain data from 1521 UT on Dec. 17 to 2326 UT on Dec. 18, 1971.

Fig. 5. Average ion energy defined in two different ways (see text) at $\approx$ 0300 local time.

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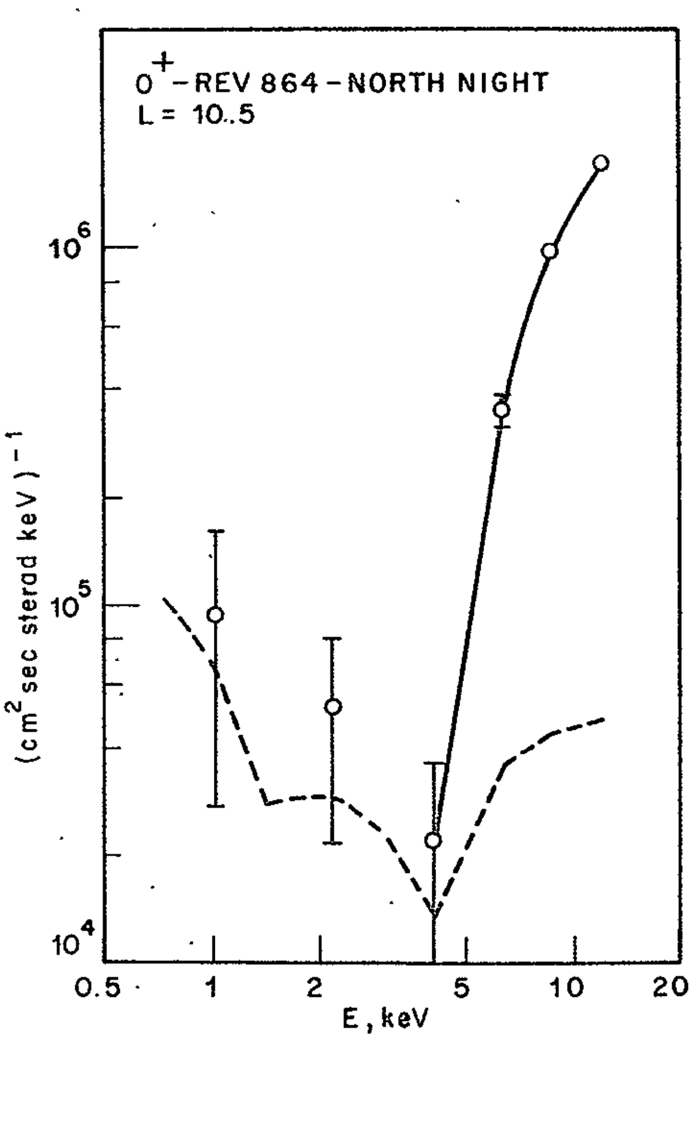
Fig. 6. Average ion energy defined in two different ways (see text) at $\approx$ 1500 local time.

Fig. 7. Contour plot of precipitating $O^+$ intensity at $\approx$ 0300 local time.

Fig. 8. Contour plot of precipitating $O^+$ intensity at $\approx$ 1500 local time.

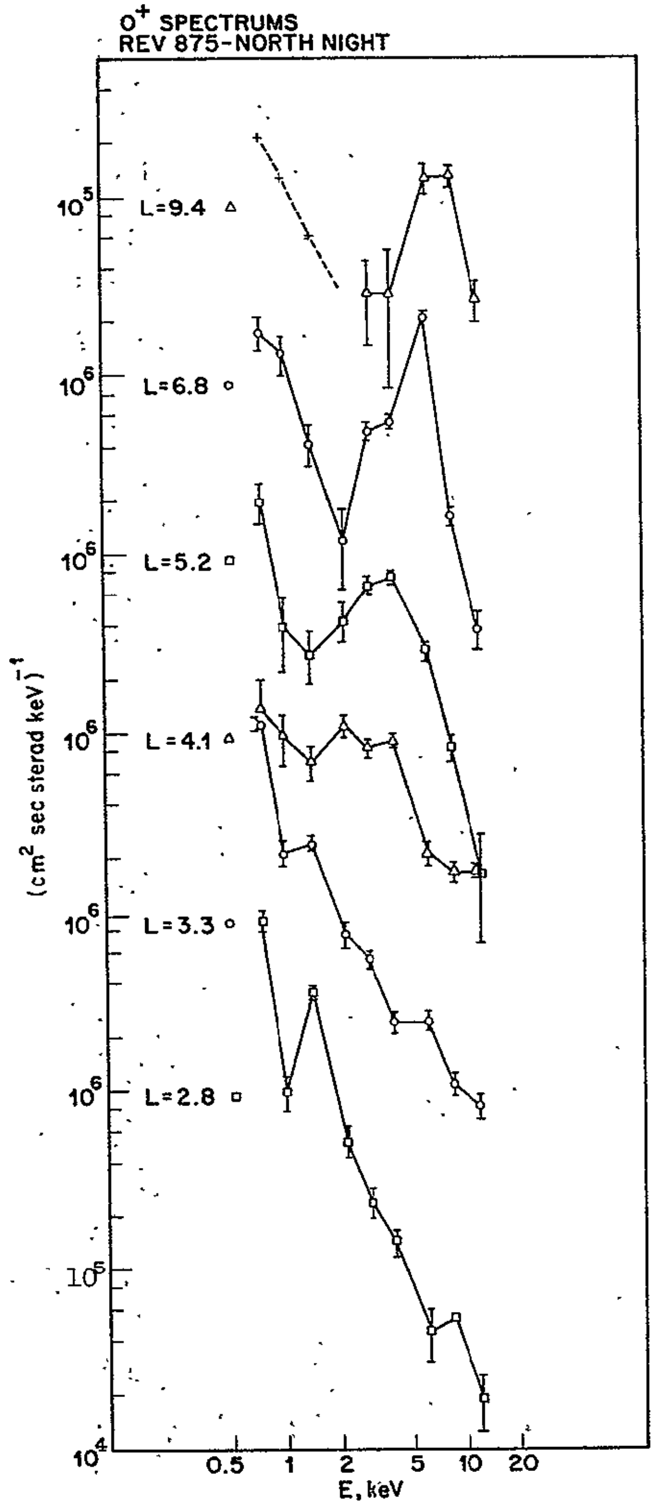
Fig. 9. Contour plot of precipitating $H^+$ intensity at $\approx$ 0300 local time.

Fig. 10. Contour plot of precipitating $H^+$ intensity at $\approx$ 1500 local time.



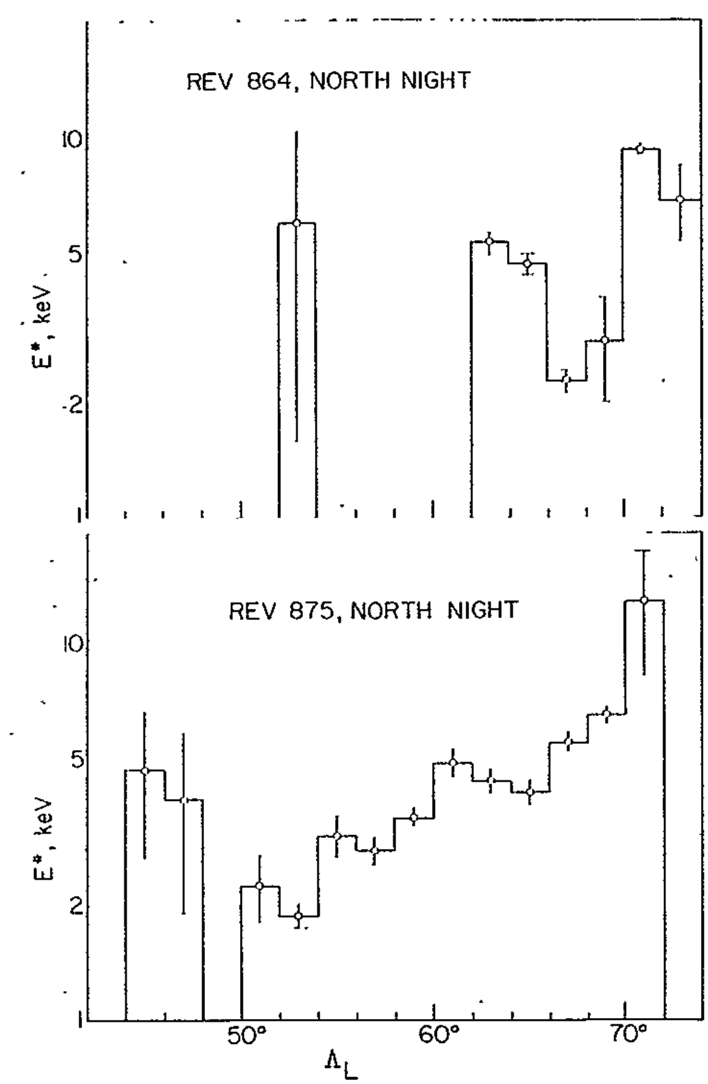
$O^+$ - REV 864 - NORTH NIGHT
L = 10.5
$10^6$
$10^5$
$10^4$
$(cm^2 sec\ sterad\ keV)^{-1}$
0.5
1
2
5
10
20
E, keV


FIGURE 1



O+ SPECTRUMS
REV 875-NORTH NIGHT
L=9.4 △
L=6.8 ○
L=5.2 □
L=4.1 △
L=3.3 ○
L=2.8 □
(cm2 sec sterad keV)-1
E, keV


FIGURE 2



REV 864, NORTH NIGHT
10
5
2
E*, keV
REV 875, NORTH NIGHT
10
5
2
1
E*, keV
50°
60°
70°
$\Lambda_L$


FIGURE 3

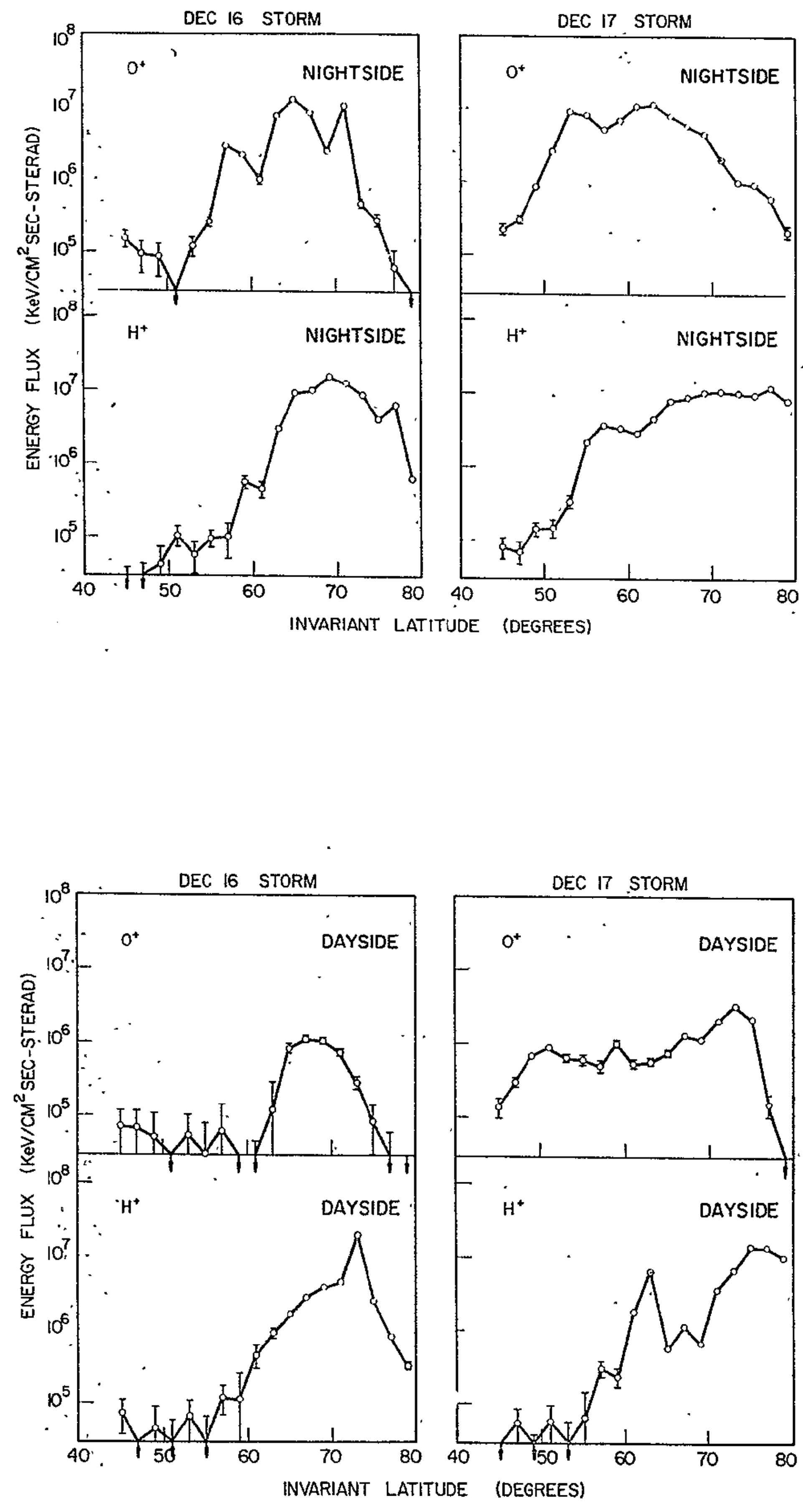

DEC 16 STORM
DEC 17 STORM
O+
H+
NIGHTSIDE
DAYSIDE
ENERGY FLUX (KeV/CM2 SEC-STERAD)
INVARIANT LATITUDE (DEGREES)

FIGURE 4

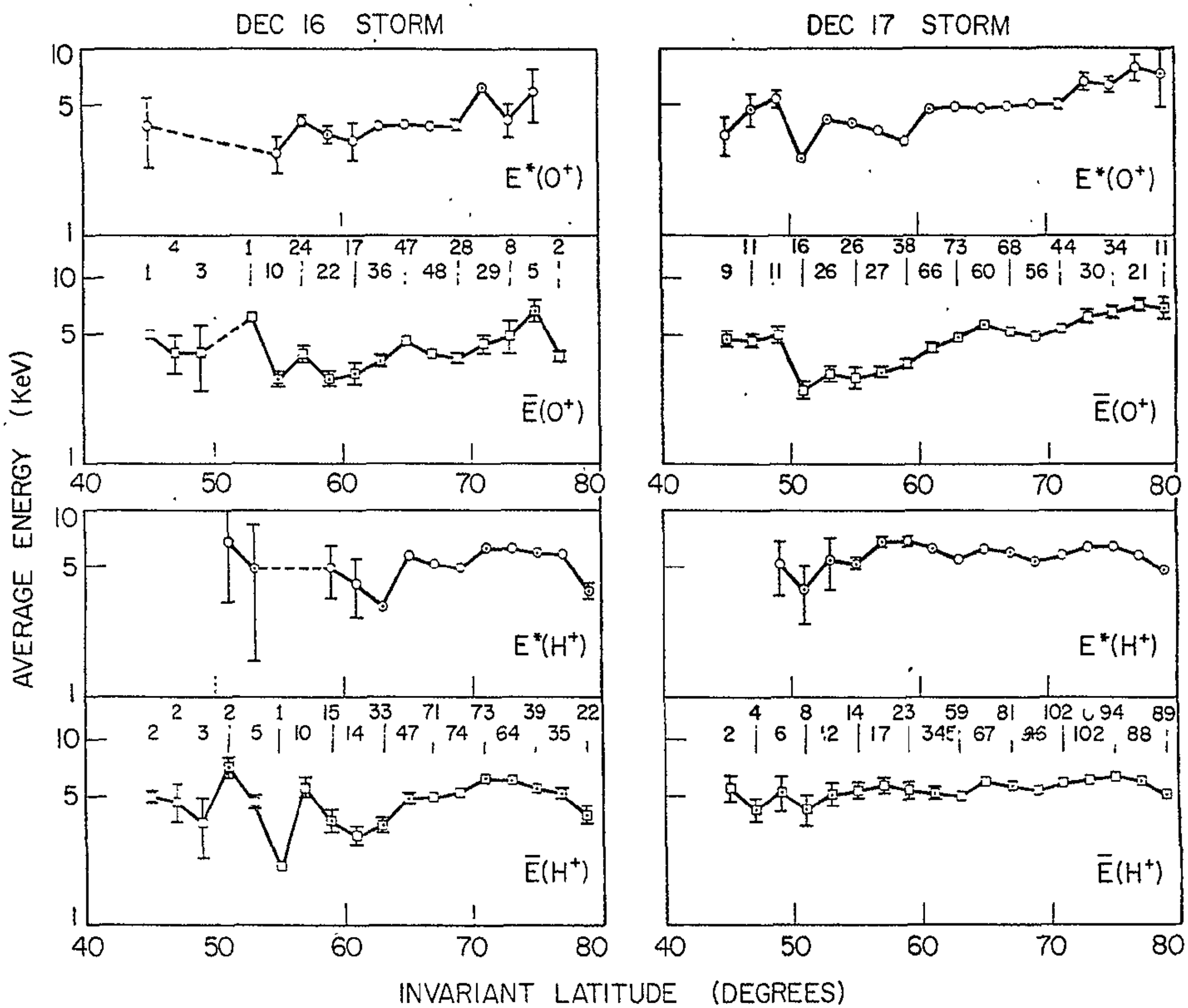
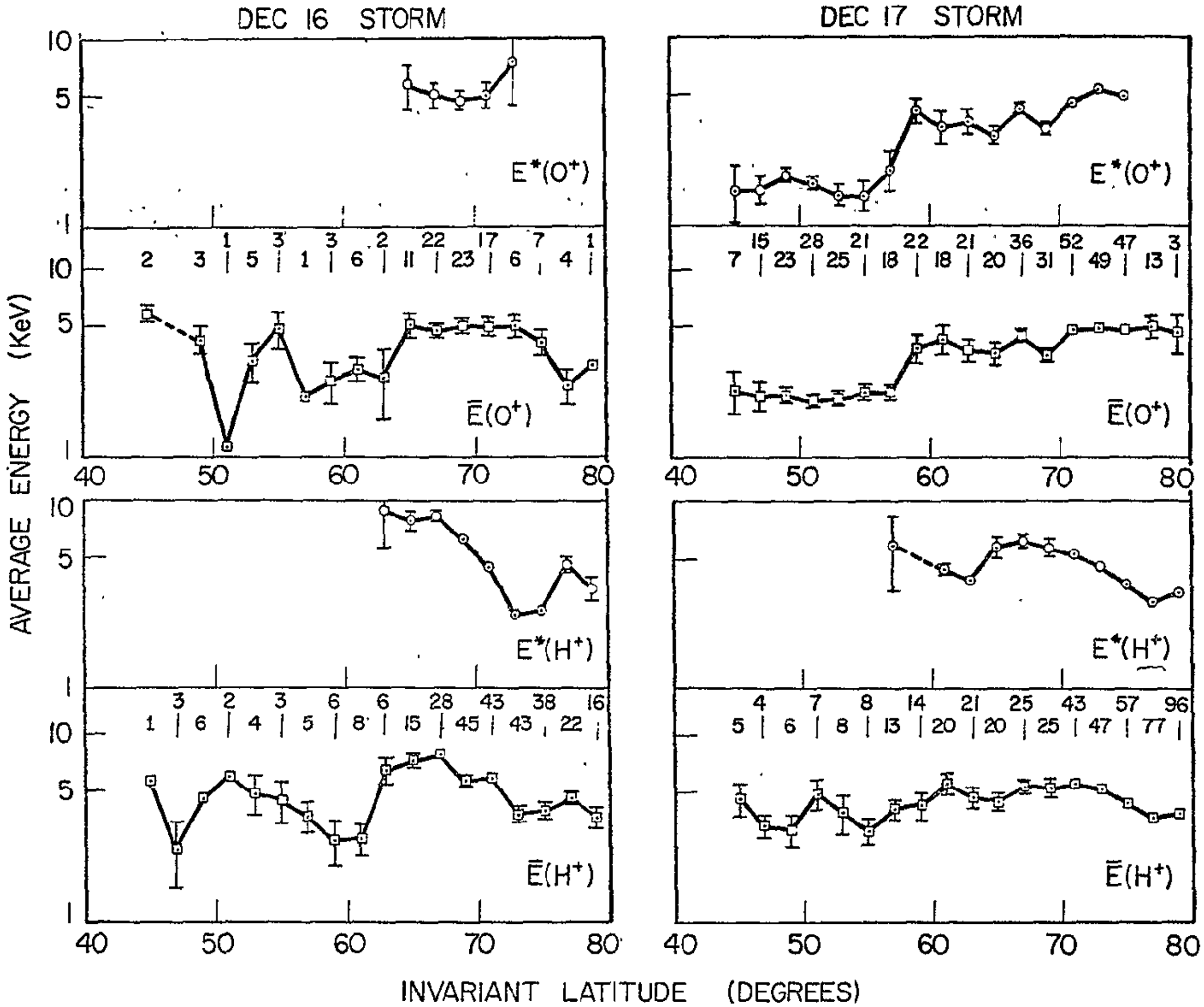

DEC 16 STORM
DEC 17 STORM
$E^*(O^+)$
$\bar{E}(O^+)$
$E^*(H^+)$
$\bar{E}(H^+)$
AVERAGE ENERGY (KeV)
INVARIANT LATITUDE (DEGREES)

FIGURE 5



DEC 16 STORM
DEC 17 STORM
AVERAGE ENERGY (KeV)
E*(O+)
Ē(O+)
E*(H+)
Ē(H+)
INVARIANT LATITUDE (DEGREES)


FIGURE 6

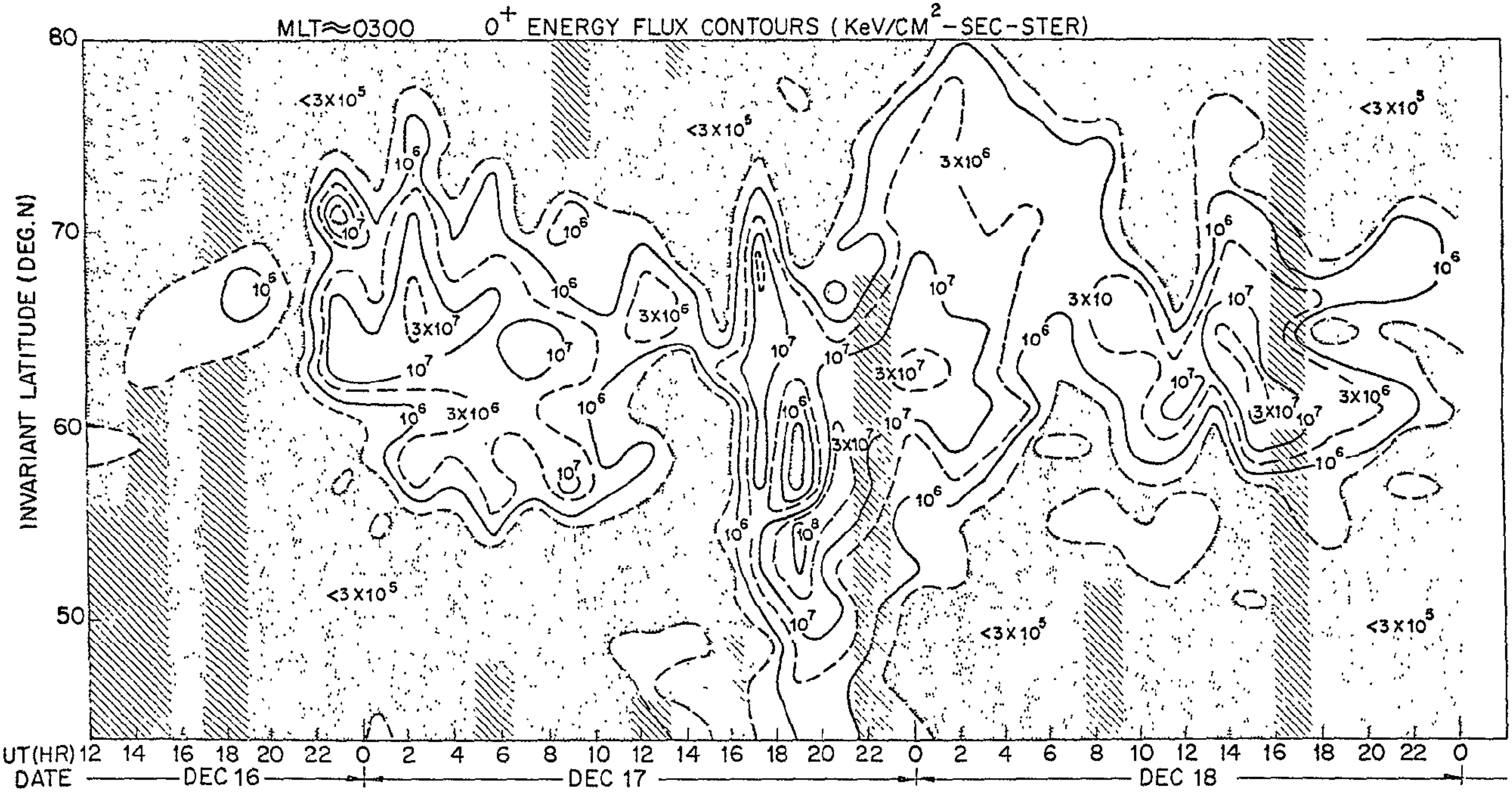
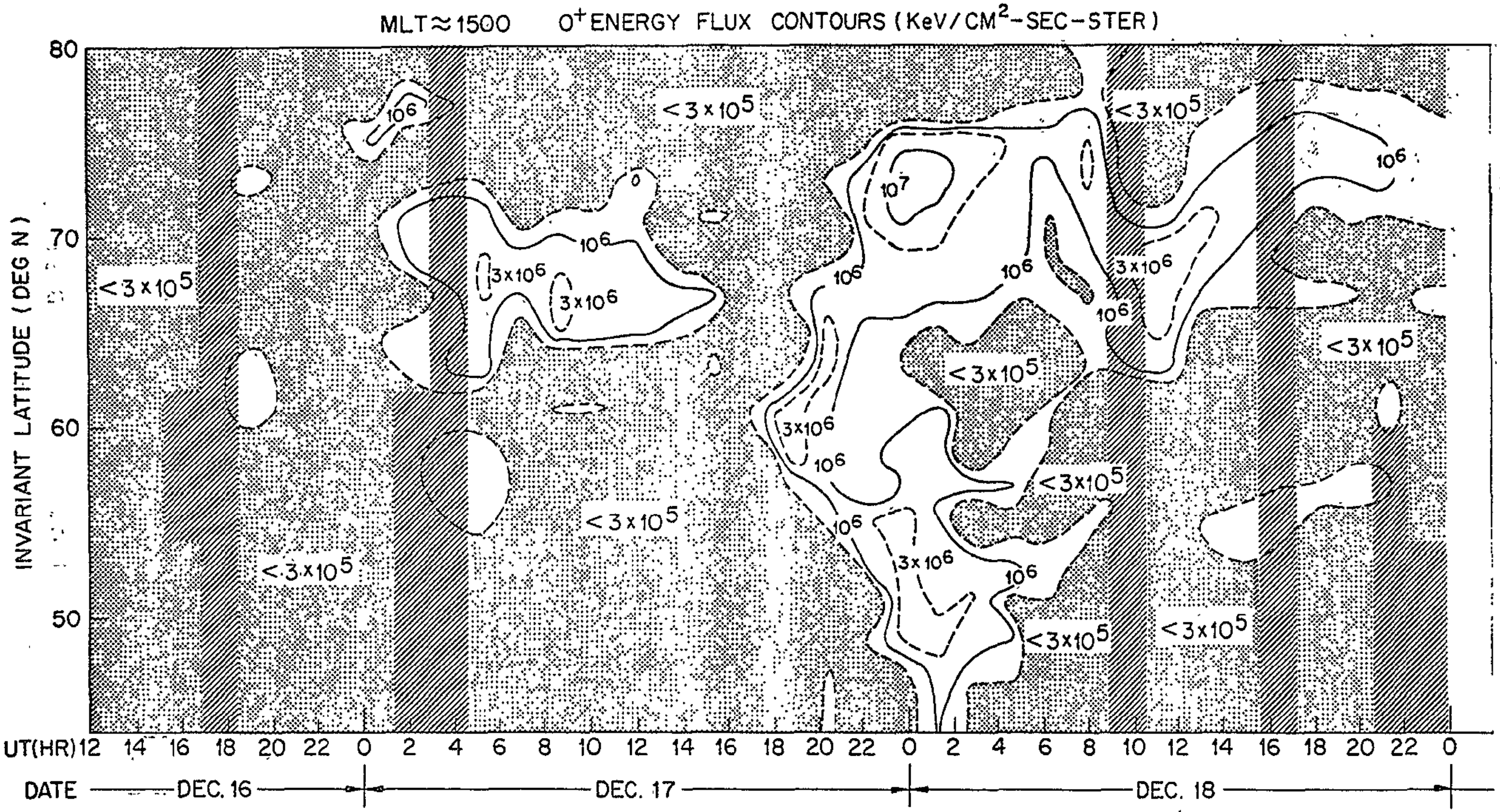

MLT≈0300 O+ ENERGY FLUX CONTOURS (KeV/CM2-SEC-STER)
INVARIANT LATITUDE (DEG.N)
80
70
60
50
<3X10^5
10^6
10^7
3X10^7
3X10^6
10^8
3X10
UT(HR) 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0
DATE DEC 16 DEC 17 DEC 18

FIGURE 7



MLT≈1500 O+ ENERGY FLUX CONTOURS (KeV/CM2-SEC-STER)
INVARIANT LATITUDE (DEG N)
80
70
60
50
<3×105
106
3×106
107
UT(HR) 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0
DATE DEC. 16 DEC. 17 DEC. 18


FIGURE 8

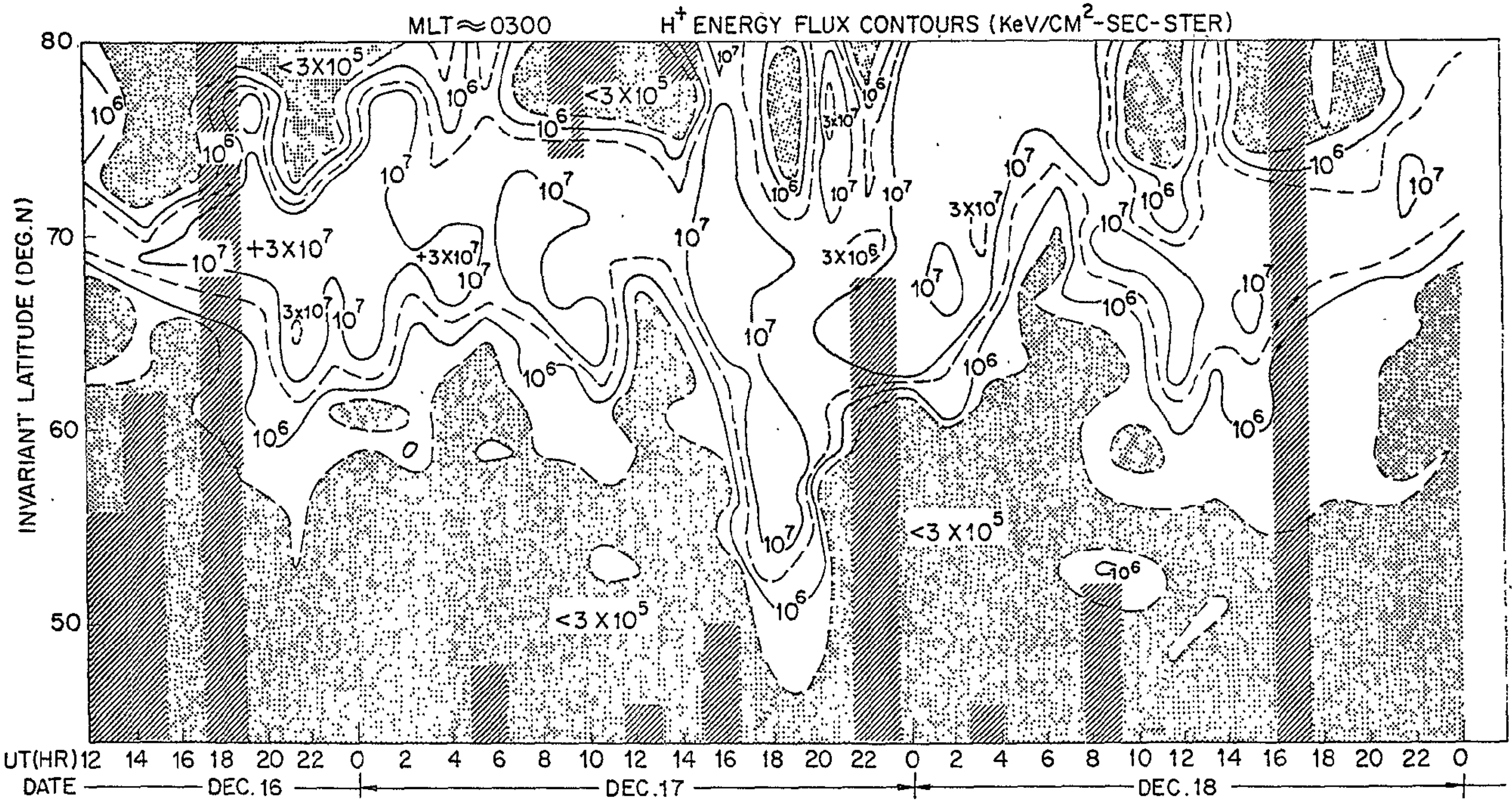

MLT ≈ 0300
H+ ENERGY FLUX CONTOURS (KeV/CM2-SEC-STER)
INVARIANT LATITUDE (DEG.N)
80
70
60
50
<3X10^5
10^6
10^7
+3X10^7
3X10^7
3X10^6
<3 X 10^5
UT(HR) 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0
DATE DEC. 16 DEC.17 DEC.18

FIGURE 9

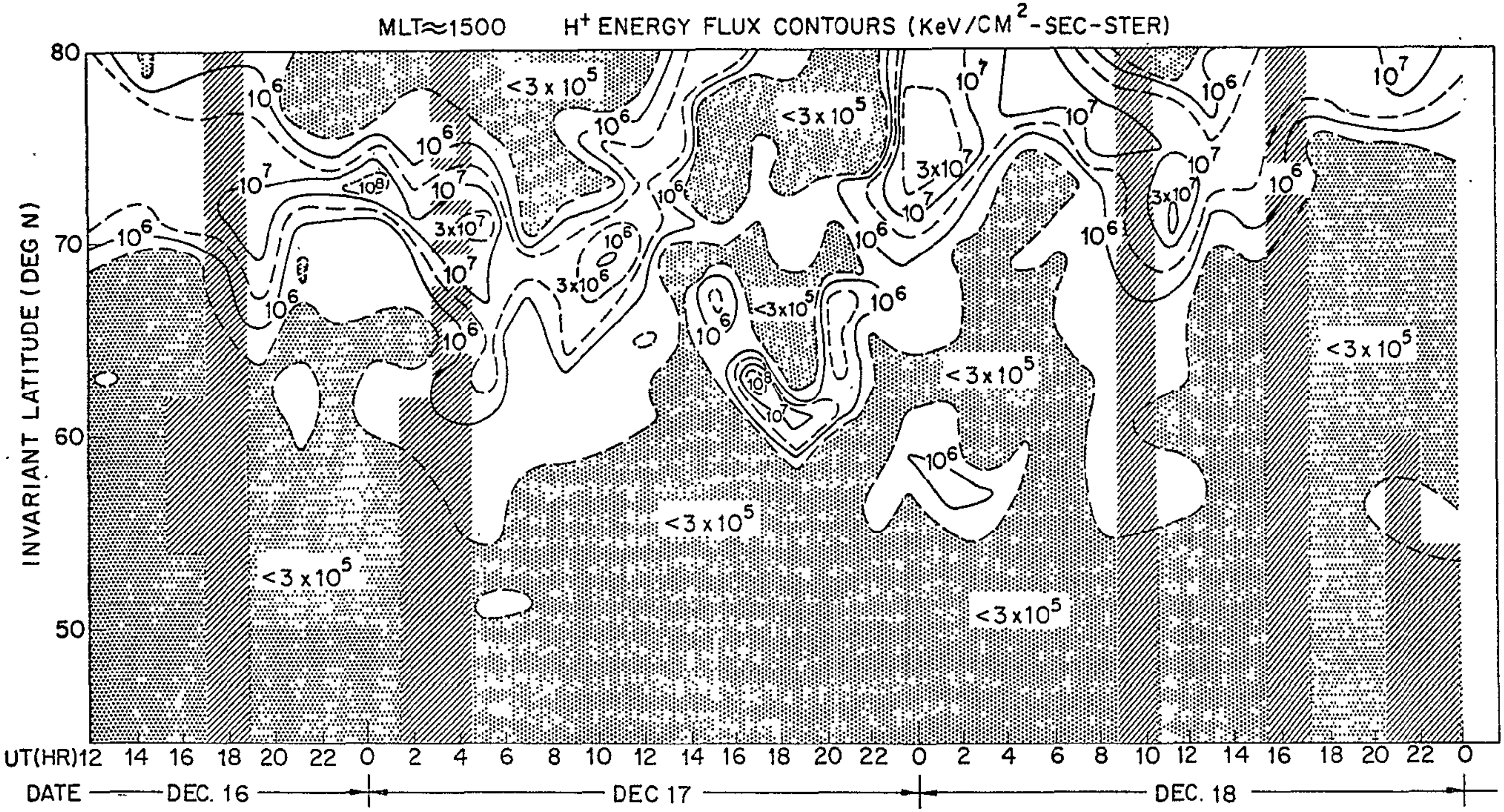

MLT≈1500 H+ ENERGY FLUX CONTOURS (KeV/CM2-SEC-STER)
INVARIANT LATITUDE (DEG N)
80
70
60
50
UT(HR)12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0 2 4 6 8 10 12 14 16 18 20 22 0
DATE DEC. 16 DEC 17 DEC. 18
<3 x 10^5
10^6
10^7
3x10^7
10^8
3x10^6

FIGURE 10

APPENDIX C

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# COMPOSITION OF THE HOT PLASMAS IN THE MAGNETOSPHERE

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## INTRODUCTION

The investigation of the mass and charge composition of the energetic (keV) plasmas in the earth's magnetosphere represents one of the most important approaches to establishing the origin of the particles in the plasmas and to understanding the complex electrodynamic processes occurring within or at the boundaries of the magnetosphere. The processes responsible for the injection, energization, transport, and loss of the plasma components are still largely unidentified and some of the processes are likely to be dependent on the mass and/or charge of the components. Thus, measurements of the differences in energy spectra, spatial distributions, and temporal behavior of the various ionic components may provide the key to identifying and characterizing the important processes. In this paper we shall limit our discussion of the composition of the energetic particles in the magnetosphere primarily to particle energies less than 50 keV. The composition measurements at higher energies and their importance in understanding the magnetospheric processes have recently been reviewed by West (1975) and Krimigis (1973).

The most plausible candidates for the source of the ionic components of the hot magnetospheric plasma are the solar wind (Meinel, 1951; Axford, 1970) and the ionosphere (Van Allen, 1962; Axford, 1970). Axford (1969, 1970) has pointed out that the measurements of the $He^3/He^4$ abundance ratio and the charge state of the energetic helium ions within the magnetosphere could be used to determine the origin of the ions. In the ionosphere the $He^3/He^4$ ratio is about $10^{-8}$ (Axford, 1969), whereas in the solar wind the ratio is in the range $10^{-3}$ to $10^{-4}$ (Bame et al., 1968). Helium is primarily doubly



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ionized in the solar wind and singly ionized in the ionosphere. The $He^3/He^4$ ratio has been measured in the auroral zone by Buhler et al. (1972) by exposing foils to the auroral ions in two rocket experiments and subsequently mass analyzing the collected ions in the laboratory. They conclude that the ions were of solar wind origin. Other abundance ratios within the magnetosphere, such as $O^+/H^+$ (Shelley et al., 1972) and $He^{++}/H^+$ (Whalen and McDiarmid, 1972) at lower particle energies and $He^+/H^+$ (Krimigis, 1973), and $C^+/O^+$ (Mogro-Compero, 1972) at higher particle energies, have also been used to infer the origin of the particles.

Processes responsible for the entry of particles into the upper magnetosphere from the ionosphere or from the solar wind may also be dependent on the mass or charge of the particles. Solar wind access to the magnetosphere through diffusive processes (Axford and Hines, 1961; Axford, 1970; Tverskoy, 1969) which depend on electric and magnetic field turbulence in the region of the magnetopause, may be dependent on the mass and charge of the particles, whereas access by merging of the geomagnetic and interplanetary fields on the dayside would at least initially provide access for all the solar wind particles. Energetic ions in the magnetosphere resulting from field-aligned flow of ionospheric ions into the magnetosphere as a result of field-aligned electric fields (Whalen et al., 1974) would be expected to reflect the composition of the ionosphere at the altitude, latitude, local time, etc., where the electric field process was operative, whereas population of the magnetospheric tail region by polar wind ions and subsequent convection deeper into the magnetosphere (Axford, 1970) would reflect the composition of the polar wind which contains $H^+$ and $He^+$ ions (Hoffman et al., 1974). Shelley et al. (1974b) have used satellite measurements of the $H^+$ and $He^{++}$ characteristics to investigate the convection electric field in the dayside cusp region at low altitudes.

The processes responsible for the energization, transport, and loss of energetic magnetospheric plasmas may often be concurrent and strongly coupled. The ability to investigate these processes as a function of the mass and charge of the plasma components whould be helpful in identifying the conditions, if any, under which the processes are weakly coupled and in investigating the processes separately or collectively. Cornwall (1972) has shown that a comparison of the radial diffusion rates of helium ions and protons in the magnetosphere would be a sensitive test of the diffusion process assumed.

In comparison to the extensive observations that are available on the electron component of the hot magnetospheric plasmas and on the total of the ionic component (usually assumed to be protons), observations which can identify the ionic species are scarce and are limited in scope. This situation has resulted from the relative complexity of the instrumentation required to make unambiguous measurements of the separate ionic components, particularly those of

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low abundance. Until the recent observations of the relatively intense $O^+$ component in the hot plasma during magnetic storms (Shelley et al., 1972, 1974a; Sharp et al., 1974a), the principal emphasis at these lower energies has been on measurements of the helium ions (Reasoner, 1973). To date the only ionic species in the hot (<50 keV) magnetospheric plasmas which have been identified and reported are $H^+$, $He^+$, $He^{++}$, and $O^+$. The $O^+$ identification is made in part on an ionospheric abudnance argument since the mass-per-unit-charge determination of 16 ± 2 AMU cannot rule out a contribution from $N^+$ ions (Shelley et al., 1972).

In view of the evidence that some of the components of the hot magnetospheric plasmas are of ionospheric origin (Shelley et al., 1972, 1974c; Sharp et al., 1974a; Johnson et al., 1974), the recent observations of Hoffman et al. (1974), on the cold plasma composition near 1400 km during the large magnetic storm on 4 August 1972, should be noted. At magnetic latitudes above 55°, they report unusually high abundances of $O^+$, $N^+$, $O_2^+$, $N_2^+$, and $NO^+$. The $N^+$ ion became the dominant species and the $O_2^+$, $N_2^+$, and $NO^+$ concentration were near $10^3$ ions/cm$^3$, which is comparable to the $O^+$ concentrations during less disturbed times. Thus, a wide range of masses of ionospheric ions at relatively high altitudes are at times available for injection into the upper magnetosphere, and the need for higher mass resolution as well as higher detection sensitivities is indicated for future energetic ion mass spectrometer measurements in the magnetosphere.

## OBSERVATIONS

### Protons

It is well established that protons are a major component of the hot magnetospheric plasma. This has been determined from ground-based observations of the Doppler-shifted hydrogen line emissions in auroral optical emission spectra (Meinel, 1951), from quantitative comparisons of ground-based measurements of the auroral hydrogen emissions with satellite measurements of the precipitating ionic component (without mass discrimination) (Romick and Sharp, 1967; Reasoner et al., 1968), and from direct measurements of the protons with energetic ion mass spectrometers on rockets (Whalen et al., 1971) and on satellites (Shelley et al., 1972; Sharp et al., 1974a). Whether protons are the dominant ionic component of the hot magnetospheric plasma at all times and all locations in the magnetosphere is now subject to question as a result of the satellite observations by Shelley et al. (1972) that the relatively large precipitating fluxes of $O^+$ ions in the energy range 0.7 to 12 keV sometimes exceeded the precipitating fluxes of protons in the same energy range during the 17 December 1971 magnetic storm. These observations are discussed in further detail in a later section of this paper.

The polar wind is a flow of ionospheric ions into the tail region of the magnetosphere and satellite measurements of the polar wind ions have been made using ion mass spectrometers (Hoffman et al., 1974). Protons, and frequently $He^+$ ions, are observed streaming outward in the high-latitude regions at velocities of several kilometers per second as determined from phase shifts in the roll modulation maximums of the sensor response between light and heavy ion species. Axford (1970) has shown that the polar wind flux is more than sufficient to provide the auroral proton flux if a magnetospheric process were operating to convect the polar wind ions from the tail region deeper into the magnetosphere and to energize them.

## $He^+$ Ions

Observations of precipitating $He^+$ ions with energies up to 1.4 keV have been reported by Johnson et al. (1974) from measurements with energetic ion mass spectrometers on two polar-orbiting satellites at altitudes of about 500 and 800 km. The $He^+$ ions, along with protons and $O^+$ ions were observed on two occasions precipitating into the auroral regions in the morning sector. No $He^{++}$ was observed on these occasions. The spatial distributions and relative intensities for one of the cases are shown in Figure 1 (from Johnson et al., 1974). The peak $He^+$ ion intensity was 0.03 erg/$cm^2$-sec-sr and occurred at L = 7 in the same region as significant fluxes of $H^+$ and $O^+$. The energy distributions of the $O^+$ and $He^+$ for this case are shown in Figure 2. It was shown from these data that the $O^+$ and $He^+$ ions had similar velocity distributions which suggests that the injection and energization mechanism may impart equal velocity to both ion species. This conclusion is highly tentative since it is based on only one event. From limits on the $He^{++}$ flux and considerations of the charge exchange processes for $He^{++}$ in the magnetosphere, the authors also conclude that the $He^+$ ions are most probably of ionospheric origin. As seen in Figure 1, the observations of protons in the same region as the $O^+$ and $He^+$ ions suggests that they might also be of ionospheric origin.

## $He^{++}$ Ions

Rocket measurements in the auroral zone of helium ions in the keV range have recently been reviewed in detail by Reasoner (1973) and will be discussed only briefly here. The most recent and most comprehensive rocket experiment to measure ion composition was that of Whalen and McDiarmid (1972) in which an instrument capable of detecting $H^+$, $He^+$, and $He^{++}$ with energies between 2 and 20 keV was flown to an altitude of about 800 km during an auroral breakup. On the basis of the charge state of the observed helium ions and the measured $He^{++}/H^+$ ratios, they concluded that the origin of the ions

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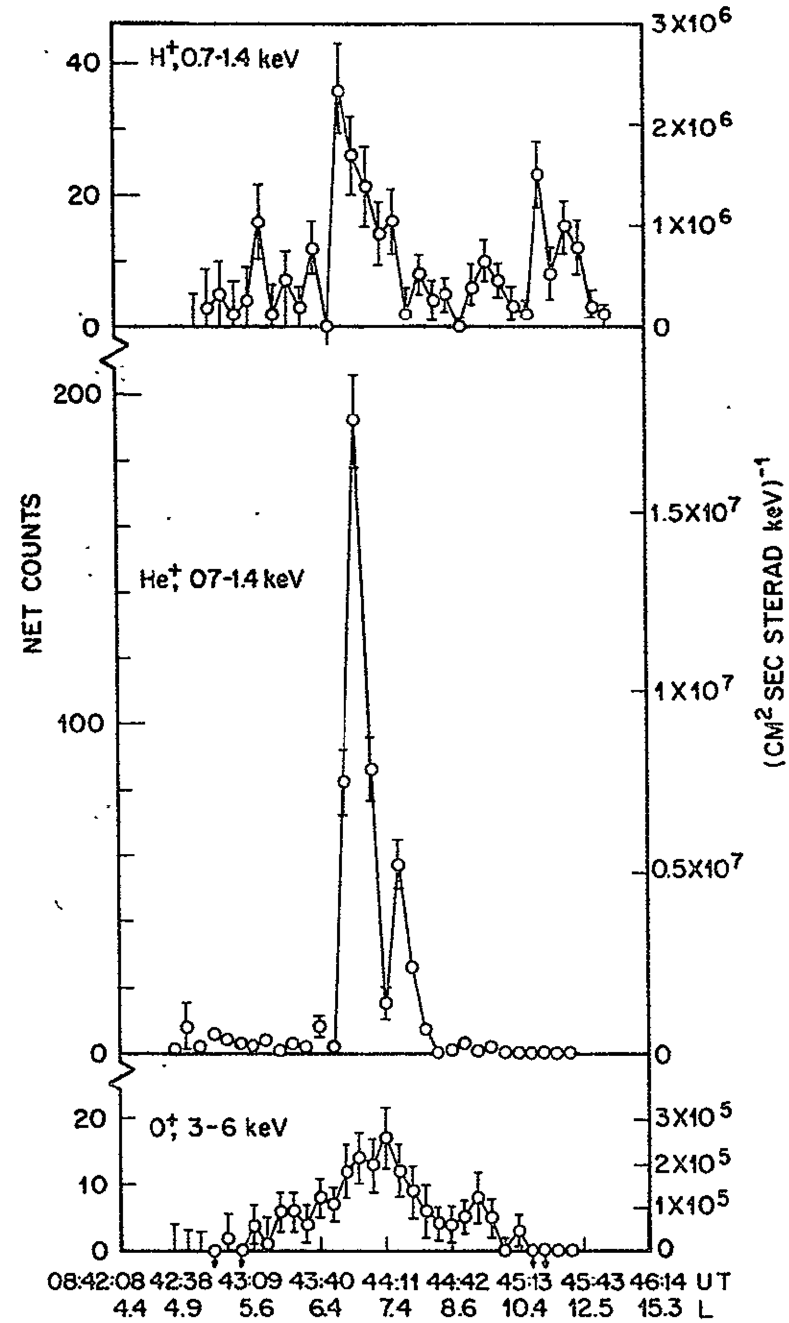


Figure 1. Latitude distributions of $H^+$, $He^+$, and $O^+$ ions.

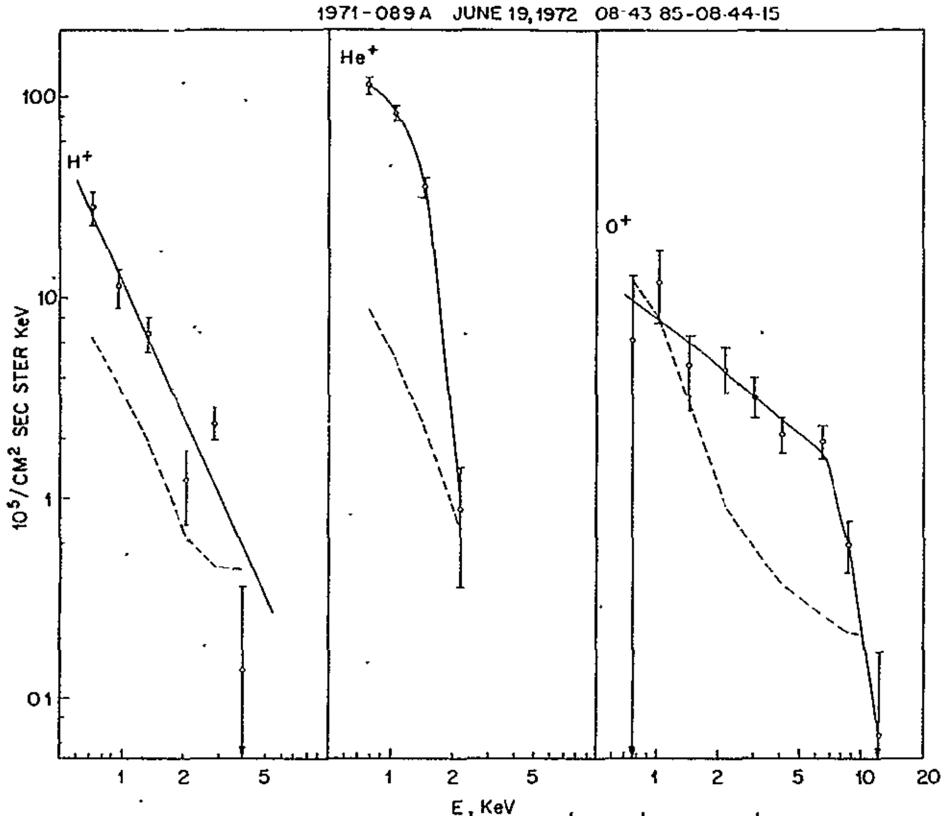


Figure 2. Energy spectrums of $H^+$, $He^+$, and $O^+$ ions.

was the solar wind rather than the ionosphere. On the basis of $He^{++}$ measurements at three energies, they also concluded that the $He^{++}$ and $H^+$ spectrums were peaked at the same energy per unit charge. From this they inferred that the solar wind ions had undergone an electrostatic acceleration of about 6 kV.

Satellite observations of $He^{++}$ have been used to investigate the convection electric field in the low-altitude region of the day-side cusp (Shelley et al., 1974b). The relative positions of the low-latitude cutoffs of the precipitating ion fluxes were found to be approximately inversely proportional to the ion velocity and independent of the ion species. The observations were consistent with a dawn-to-dusk electric field of about 50 mV/meter.

Energetic $He^{++}$ ions have been observed from satellite measurements precipitating into the nightside auroral region during a magnetic storm (Sharp et al., 1974b). The precipitation was observed over a wide latitudinal region from L = 3.8 to L = 7.5 and the aver-

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aged $He^{++}/H^{+}$ ratio varied from 5.6 ± 0.7% at L = 7.3 to 2.9% ± 0.5% at L = 5.0. The velocity distributions of the $H^{+}$ and $He^{++}$ were surprisingly similar as seen in Figure 3 (from Sharp et al., 1974b). From considerations of the observed $He^{++}/H^{+}$ ratio which is typical of the solar wind and from the similarity of the velocity distributions, it was concluded that the $He^{++}$ and $H^{+}$ originated in the solar wind and were acted upon within the magnetosphere by adiabatic processes and that no substantial electrostatic acceleration occurred. It should be noted that in this case the inferred acceleration process is different from the electrostatic acceleration process inferred from the rocket measurements of Whalen and McDiarmid (1972). Of course, multiple acceleration processes within the magnetosphere are not excluded.

## $O^{+}$ Ions

$O^{+}$ Ions During Substorms. The precipitating energetic $O^{+}$ ions during the substorms on 12 and 13 December 1971 have been investigated using data acquired with the energetic ion mass spectrometer aboard the polar-orbiting satellite 1971-089A at an altitude of about 800 km. The instrument was oriented at 55° to the zenith during all the measurements and thus sampled only the precipitating ion fluxes at the high latitudes of the $O^{+}$ data discussed here. It covered the energy range in nine steps from 0.7 to 12 keV and the mass-per-unit-charge range from 1 to 32 AMU (Shelley et al., 1972).

The magnetic activity on 12 and 13 December 1971 is indicated by the bottom two curves in Figure 4. Prior to 1500 hours on 12 December, $K_p$ was less than 2 and AE was less than 100 gammas. Two fairly well isolated substorms are indicated by the AE index. The second of these, beginning at about 2200 hours, has been investigated by Williams et al. (1974) using Explorer 45 data acquired in the pre-midnight local time sector. The second substorm was widespread in local time and was observed at Dixon Island (0320 LT) in the local time sector of the satellite measurements. Investigation of the details of the first substorm are not yet complete.

The peak intensities of the $O^{+}$ ions are shown by the top curve in Figure 4. During the quiet magnetic period prior to 1500 on 12 December, the $O^{+}$ intensities were near or at the limit of the sensitivity of the instrument. Beginning at 1600 hours, the $O^{+}$ ions are observed in the local morning sector during each available satellite pass for a period of 12 hours and the general correlation with the substorm activity as indicated by the AE index is quite evident. Larger intensities were observed in the second substorm, but the peak fluxes of the first storm may have been missed because of the limited time coverage provided by the satellite measurement. The spread in local time of the $O^{+}$ observations was from 0200 to 0500 hours.

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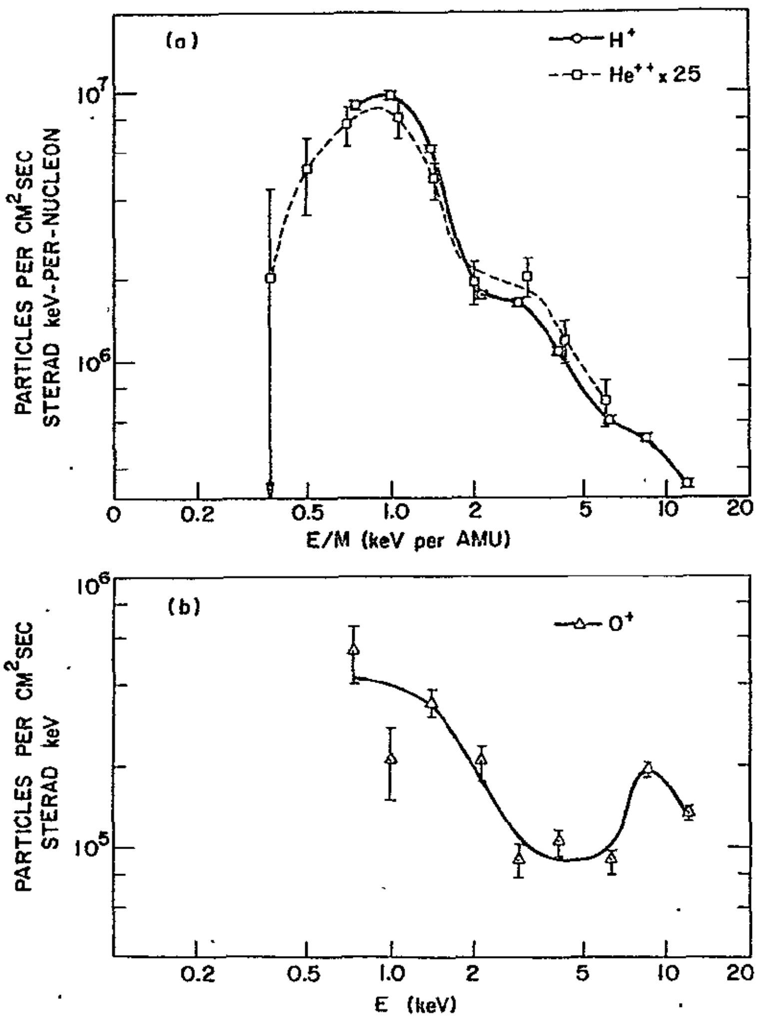


Figure 3. a) Energy per nucleon spectrums of $H^+$ and $He^{++}$ ions.
b) Energy spectrums of $O^+$ during the same period.

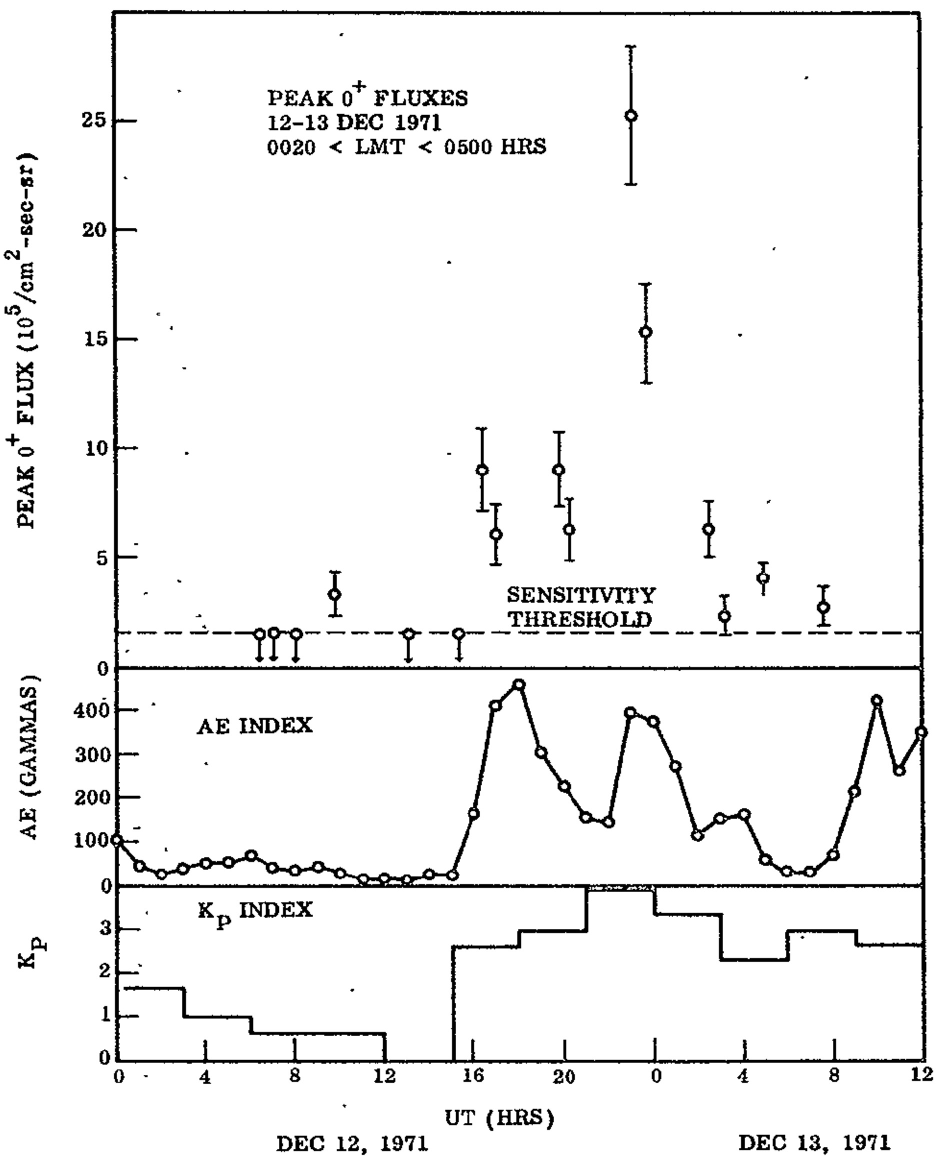


Figure 4. Peak $O^+$ fluxes measured during two substorms.

The mean width of the regions of precipitation, defined by the 10% and 90% points of the integral of the number flux as the satellite traverses the region of $O^+$ precipitation, was found to be 2.5 degrees in magnetic latitude. The location of the mean position of the $O^+$ region, defined by the 50% point of the above integral is compared in Figure 5 with the location of the lower-latitude edge of the proton flux measured with the same instrument over the same energy range, 0.7 to 12 keV. The low-latitude edge of the protons is generally a distinctive feature of the data and is defined in this study as the lowest latitude at which 50% of the peak proton number flux in the plasma sheet particle region is observed. A strong correlation between these positions is seen in Figure 5, and the mean position of the $O^+$ fluxes is generally equatorward of the proton edge. During these substorms, the mean position of the $O^+$ fluxes was also always inside the "cut-off" trapping boundary for energetic electrons as defined by Romick et al. (1974) for electrons with energies greater than 130 keV.

From this study and from synoptic studies of other substorms with less complete data coverage, it is concluded that precipitating $O^+$ ions are a common feature of magnetic substorms.

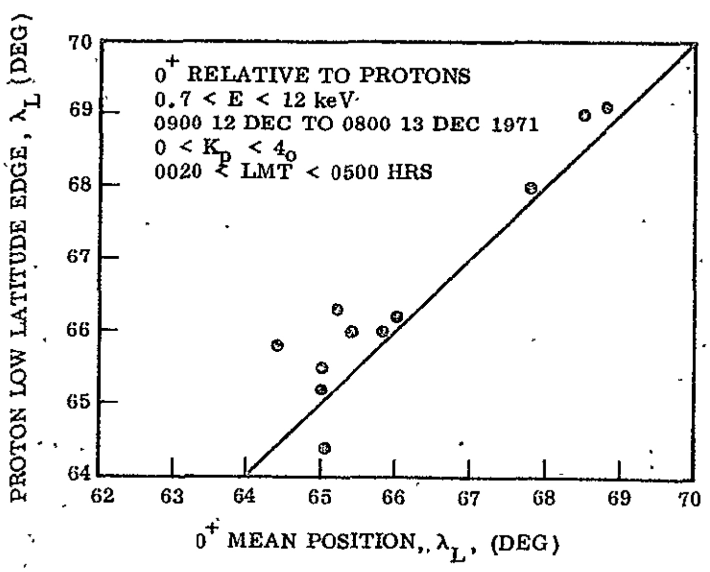


Figure 5. Relative locations of $O^+$ and $H^+$ fluxes during the time period shown in Figure 4.

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The Morphology of Precipitating $O^+$ Ions in a Magnetic Storm. In order to search for clues to the nature of the processes which accelerate the $O^+$ ions from the cold ionospheric plasma and to define as closely as possible the morphological parameters which the theories will have to explain, a detailed study of the morphology of the $O^+$ ions during the 17-18 December 1971 magnetic storm is being conducted and some preliminary results of that study are presently available. This was a rather classic magnetic storm with an ssc at 1418 UT on 17 December and a large main phase. The peak $D_{ST}$ was 171γ and the storm lasted until about 2300 UT on the 18th. The satellite was in the 0300/1500 LT plane during the period of interest and a rather high fraction of data coverage was being obtained, which provided about as good temporal resolution as can be achieved for studies such as this with a polar-orbiting satellite. Figure 6 from Shelley et al. (1972) shows the data from 6 consecutive satellite traversals of the nightside (0300 hours LT) auroral and subauroral regions during the main phase of the storm. Data for both $H^+$ ions (solid curve and closed circles) and $O^+$ ions (dashed curve and open circles) are illustrated. The ordinate is the total number of counts in the mass-per-unit-charge peak for the appropriate species summed over all nine of the energies sampled in a complete 6-second cycle of the experiment. It is approximately proportional to the integral number flux in the $0.7 \le E \le 12$ keV range.

The principal features of note in Figure 6 are: 1) the peak $O^+$ fluxes are comparable to or greater than those of the protons in the energy range measured; 2) the $O^+$ ions are observed over a wide latitude range implying either an extended source or precipitation from a trapped population undergoing substantial radial diffusion; 3) the fluxes of both species are highly structured with respect to latitude and quite variable from one pass to the next with no obvious specific conjugate structure; and 4) the $O^+$ ions are spatially displaced with respect to the protons, i.e., they generally extend equatorward of the protons and the protons generally extend poleward of the $O^+$ ions.

For the detailed morphological study mentioned above, we have formulated several different parameters from data such as is illustrated in Figure 6 and have intercompared these parameters with each other as a function of magnetic latitude and time during the course of the storm, and with various indices of geomagnetic activity. For an intensity parameter characteristic of an entire satellite traversal of the auroral and subauroral regions, we computed the integral energy flux of the $O^+$ ions over the latitudinal range $44^\circ < \Lambda_L < 80^\circ$. This quantity is illustrated in Figure 7 for the northern hemisphere data only. For comparison we have plotted the $D_{ST}$ index on the same logarithmic scale, but inverted so that increasing ring-current intensity corresponds to an increasing value of the ordinate. One sees that there is a remarkable quantitative correlation between these quantities over the period illustrated. The initial rise

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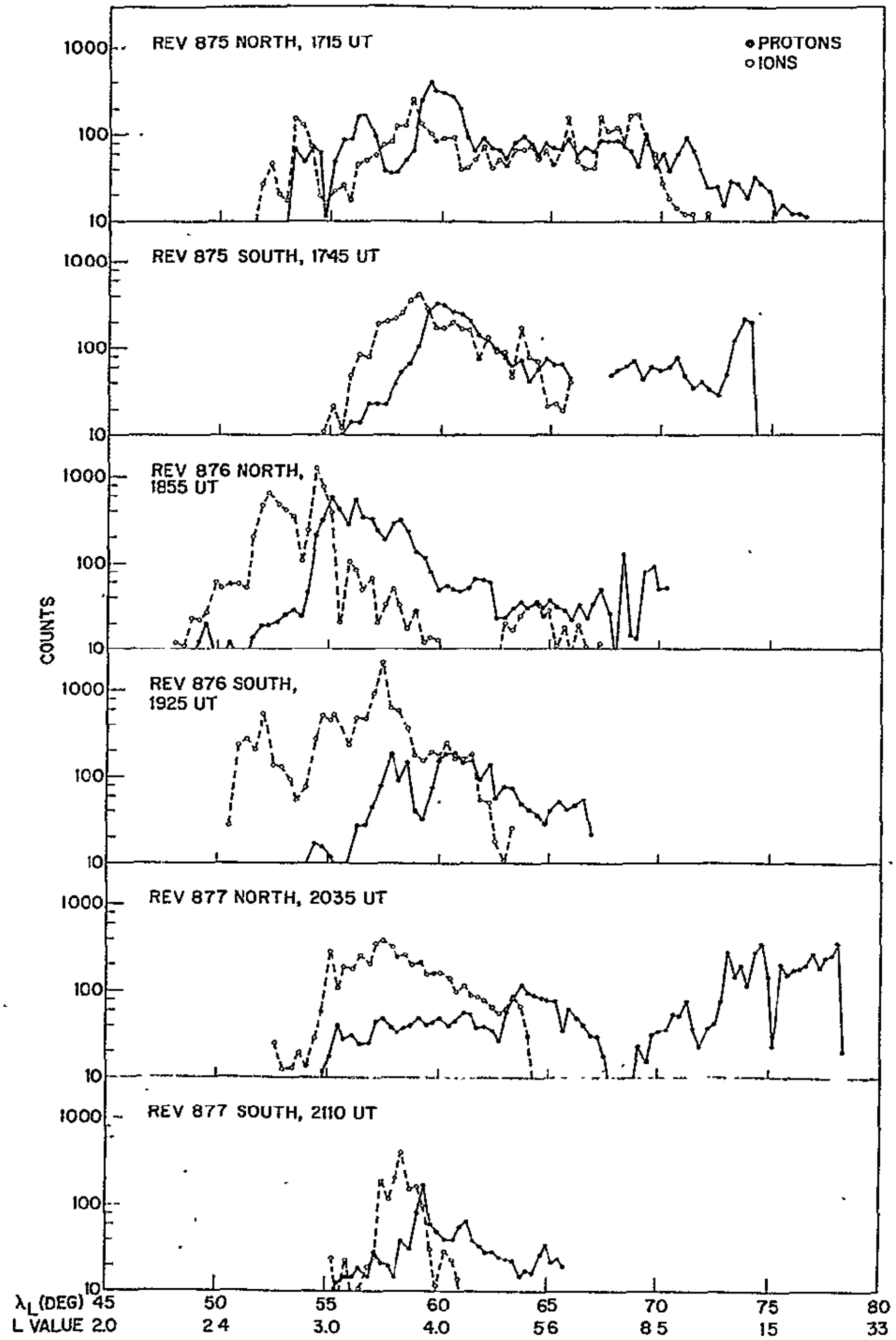


Figure 6. Ion fluxes during the 17 December 1971 magnetic storm.

after the ssc at 1418 is about the same in both the timing and relative amplitudes. The $O^+$ intensities appear to have a substantially shorter decay time than the ring current. This trend is also exhibited by the earlier data from remnants of the 16 December storm (ssc at 1904 UT) which was still in progress at the onset of the 17 December event. The close correspondence of the two illustrated quantities can be interpreted in several ways. It can be considered to support the hypothesis of Cladis (1973a,b) that the energy for the acceleration of the $O^+$ ions is derived from the ring-current particles. Alternatively, one could formulate a model in which a significant fraction of the ring current itself is in the form of $O^+$

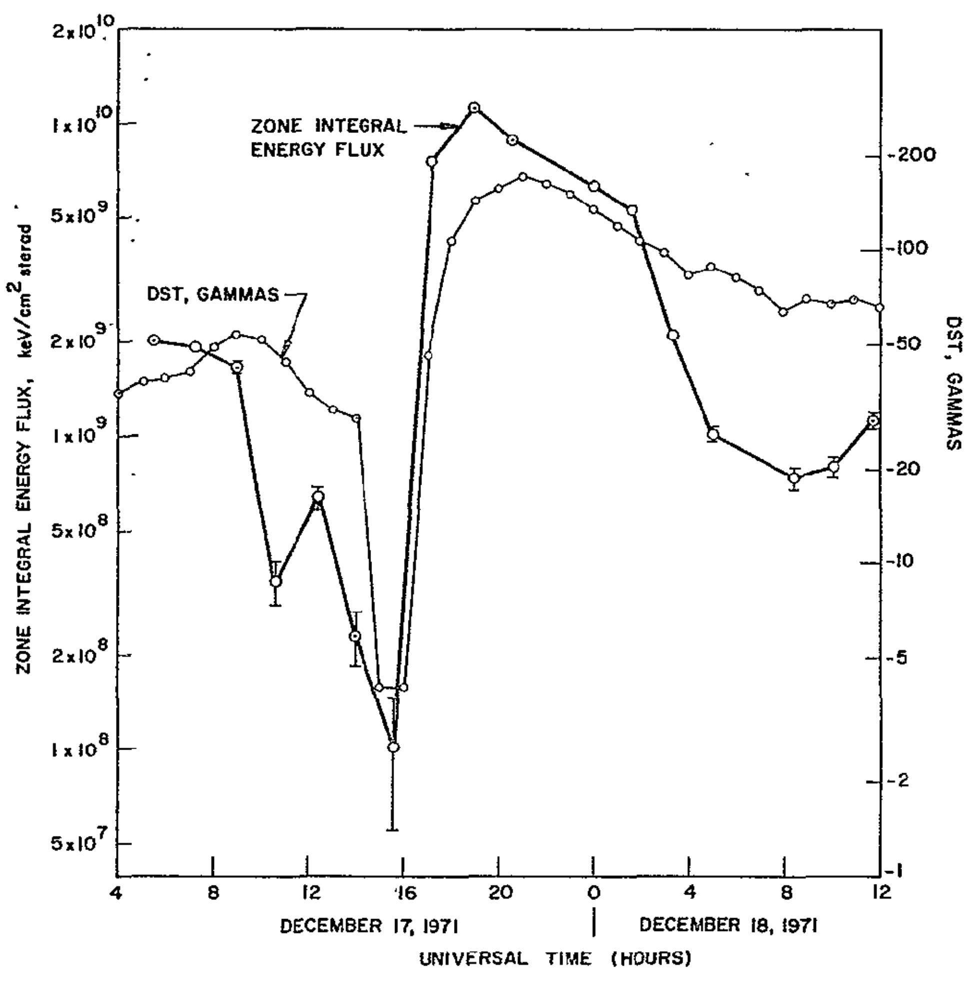


Figure 7. Integral $O^+$ intensity compared to $D_{ST}$.

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ions and the time dependence of the observed precipitation reflects the varying flux intensity of the parent trapped population.

Figure 8 from Shelley et al. (1972) shows some representative energy spectrums from one of the passes illustrated in Figure 6 (Revolution 876 - South). The data are averaged over the time intervals indicated. The error bars represent counting statistics only. The spectrums vary from a monotonically steeply falling one at low latitudes to a hard spectrum with a peak at about 4 keV at high latitudes. Peaks in the few-keV range are a common feature of the $O^+$ spectrums which have been examined up to this time and, as will be seen below, the general trend of a spectral hardening with increasing latitude has been found to be typical for the storm in question.

Data from another nightside pass at 1714 UT illustrating this trend are shown in Figure 9. This pass marked the initial flux increase after the ssc and thus might be expected to have a spectral signature most representative of the injection mechanism before distortions due to drift effects could obscure any discernible trends. For this pass the average energy of the $O^+$ ions in the $0.7 \leq E < 12$ keV range has been computed in $2^\circ$ latitudinal intervals. The error bars represent counting statistics only. The average energy was considered significant and formulated only in latitudinal intervals in which the average energy flux was $\geq 10^6$ keV/cm$^2$-sec-sr. It was computed by taking the ratio of the energy flux to the number flux, each of which had been averaged over the $2^\circ$ latitudinal interval, and thus tends to be weighted by the more intense events within the interval. An alternative computation was performed by computing the average energy from those individual (six-second) spectral measurements that were considered statistically significant and then taking the average value of these quantities over the $2^\circ$ interval, weighting each measurement equally. The significance criterion chosen was that the integral number flux in the individual spectrum had to be $\geqslant$ twice its standard deviation. The latitudinal dependence of this parameter computed from the northern nightside data throughout the time period 0532 UT on 17 December to 1146 UT on 18 December (cf Figure 7) is given in Figure 10. The error bars in this figure represent the standard deviations of the means of these individual average energies and not counting statistics. A similar plot prepared from the average energy values computed according to the definition utilized in Figure 9 give similar results, indicating that the observed trend is not the result of biasing due to a specific weighting technique. Thus, we see that the rather surprising trend of a spectral hardening with increasing latitude is characteristic of this entire period. Radial diffusion processes such as discussed by Nakada et al. (1965) would be expected to produce an opposite effect. Hopefully, this will be a useful morphological feature with which to test specific theoretical models.

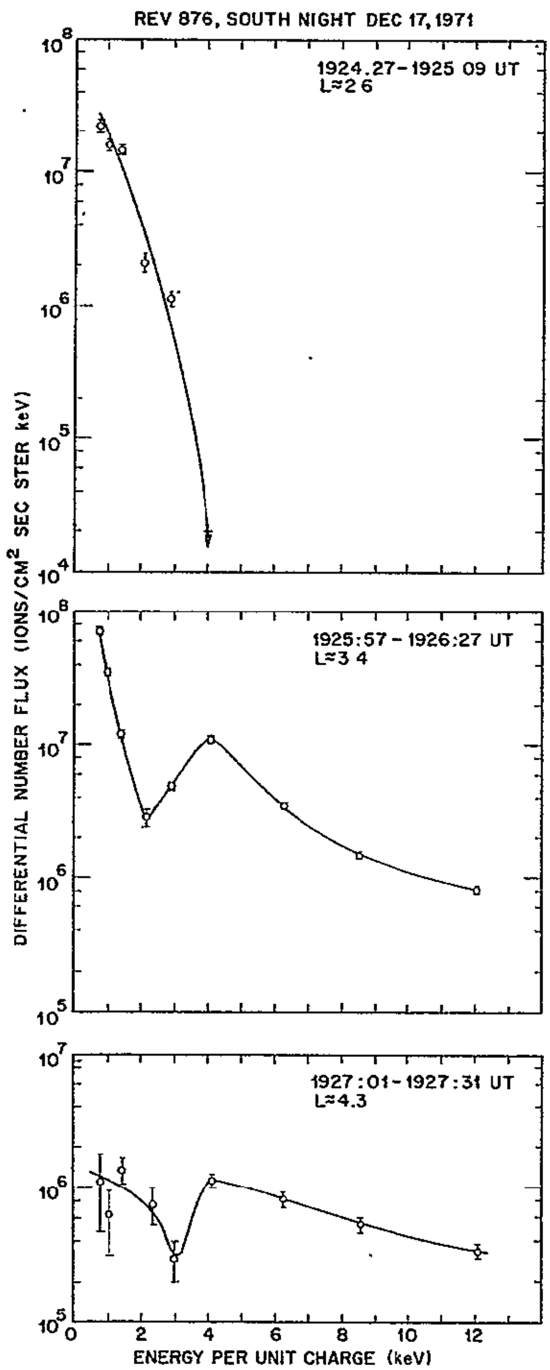


Figure 8. Energy spectrums of $O^+$ ions.

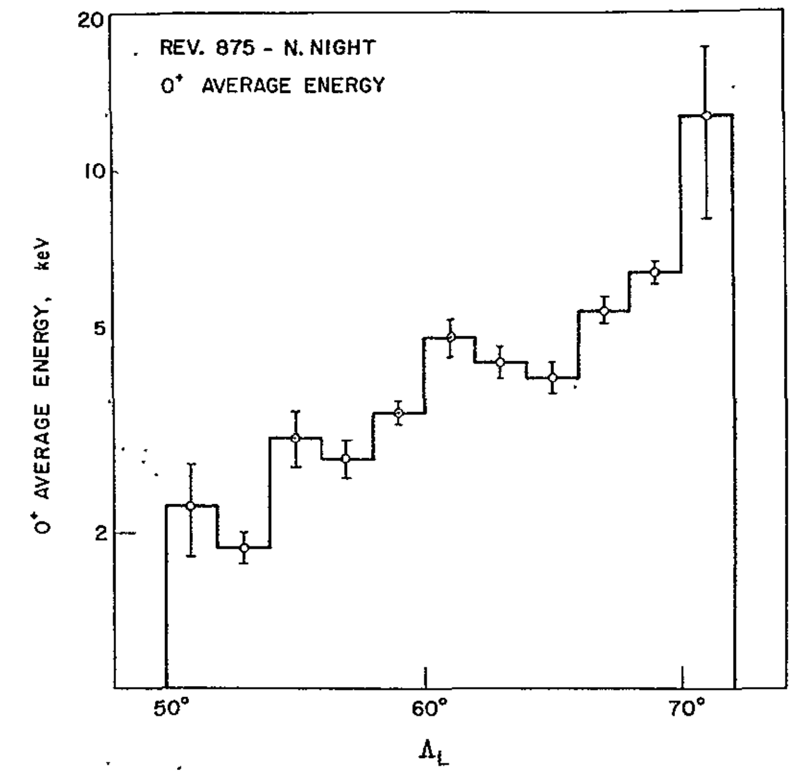


Figure 9. Latitudinal variation of the average energy of $O^+$ ions on a single pass.

The latitudinal variations of the $O^+$ and $H^+$ precipitation patterns during this period also exhibit some interesting characteristics. In Figure 11, the center of the observed precipitation region, measured by the 50% point in the zone integral intensity parameter described in connection with Figure 7 is indicated with a circle for $H^+$ ions and a square for $O^+$ ions. The horizontal bars represent the extent of the precipitation region measured by the 10% and 90% points in this same parameter. In several instances during this period, the proton precipitation extended well into the polar cap. The satellite orbit on some passes did not extend higher than 80° invariant latitude so in order to form a uniform data base, we truncated the zone integrals at that latitude. Thus, for those points in Figure 4 in which the upper bar is in the vicinity of 78°-80°, that point does not in general mark the extreme upper latitude of the precipitation region. Despite this distortion, we see a remarkable tracking of the precipitation zones of the two ions with a latitudinal displacement of about 5° as suggested by the data in Figure 6. This detailed tracking illustrates the intimate relationship between

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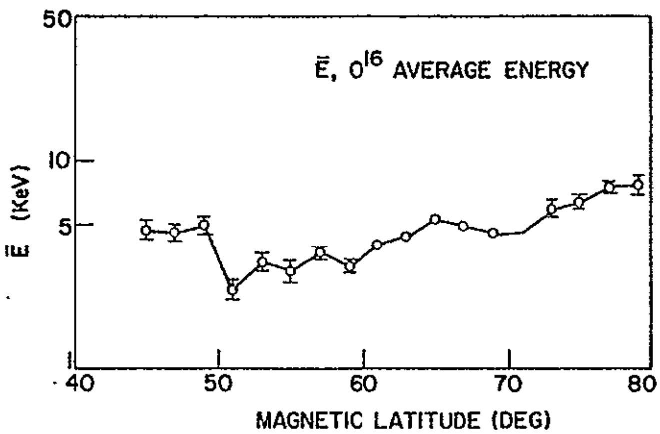


Figure 10. Latitudinal variation of the average energy of $O^+$ ions during the time period shown in Figure 7.

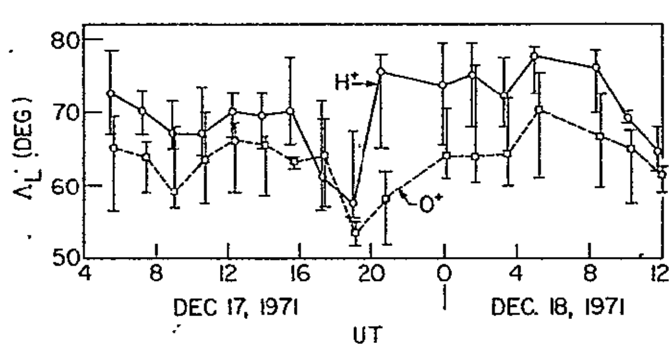


Figure 11. Locations of the precipitation zones of $O^+$ and $H^+$ ions.

the $O^+$ ions and the magnetospheric proton population in the energy range measured.

The overall latitudinal dependence of the precipitation intensity during this entire period (0532 UT on 17 December to 1146 UT on 18 December) is shown in Figure 12. We see most clearly in this figure how the $O^+$ ions provide the dominant part of the precipitating energy flux in this energy range over a substantial latitudinal interval. The latitudinal displacement of the two zones is evident and as indicated above one sees that the high-altitude extent of the $H^+$ precipitation region extends into the polar cap (i.e., $\Lambda_L > 80°$), while the $O^+$ is more nearly confined to the auroral zone and the subauroral regions of the trapped outer radiation belt particles.

Synoptic Study of $O^+$ in Magnetic Storms. In order to investigate the local time dependence of the $O^+$ precipitation, a synoptic study was made of the data from one year's operation of the energetic (0.7 to 12 keV) ion mass spectrometer aboard the 1971-089A satellite (Shelley et al., 1974a). During this period the satellite precessed

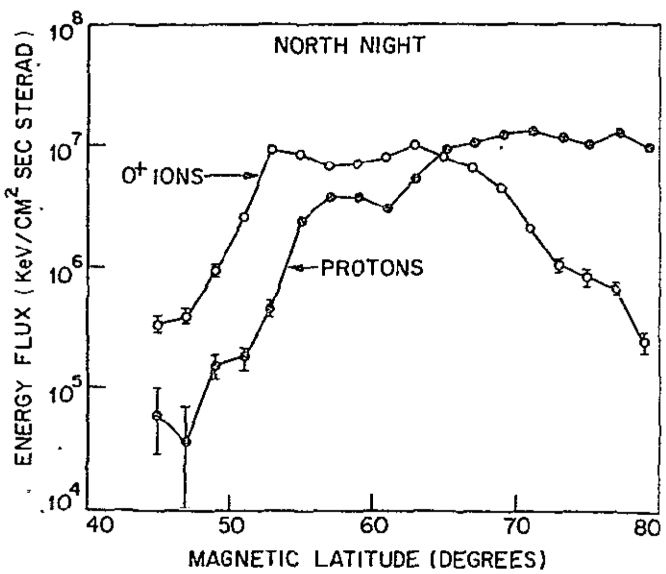


Figure 12. Latitudinal variation of the energy flux of $O^+$ and $H^+$ ions during the time period shown in Figure 7.

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through the entire range of local times. Eleven of the principal magnetic storms in the period from December 1971 to November 1972 were utilized. Data from three orbits were examined for each storm, selected from the beginning, middle, and end of the storm being studied. $O^+$ ions were observed precipitating into the atmosphere during every storm.

Figure 13 shows the latitudinal extent of the $O^+$ precipitation regions. The dot indicates the position of the maximum flux intensity on each pass and the lines indicate the portion of the pass during which the flux was greater than the spectrometer sensitivity threshold of $\approx 2 \times 10^5$ ions/cm$^2$-sec-sr.

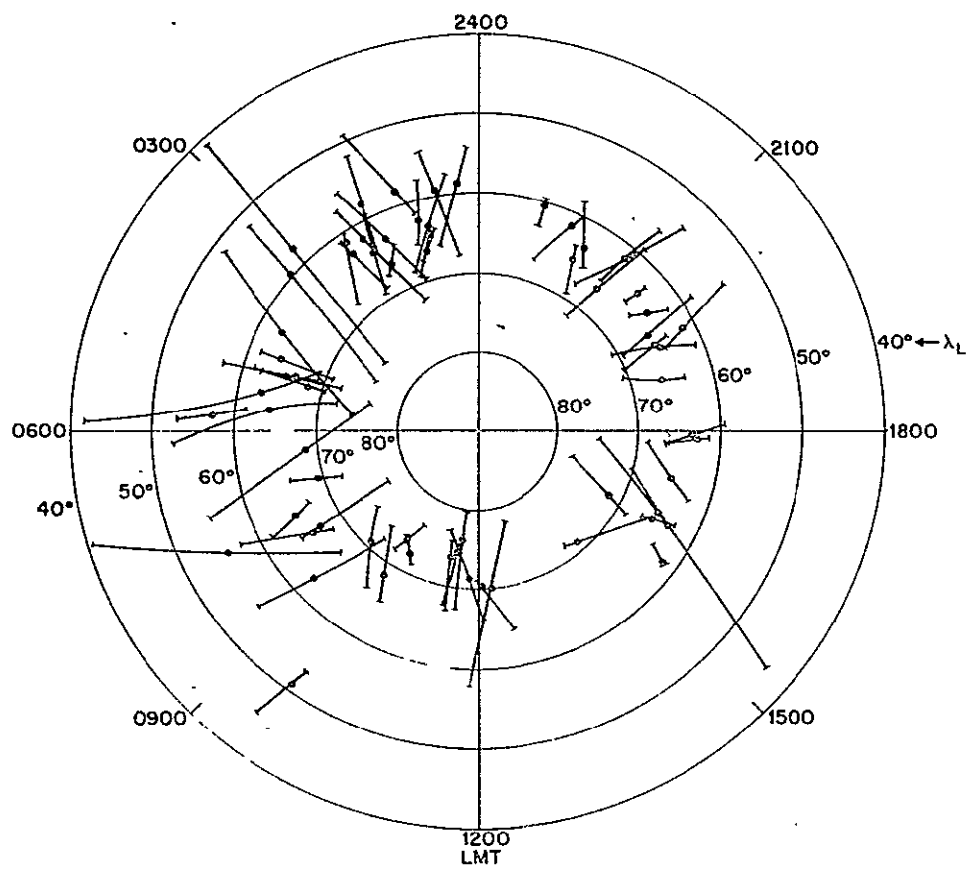


Figure 13. Polar plot in invariant latitude and magnetic local time of the regions of observed $O^+$ precipitation during 11 major storms.

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The peak flux intensities are shown in Figure 14. The solid horizontal bars indicate the median values in each three-hour sector of magnetic local time. For comparison with typical auroral proton intensities, we have indicated with a dashed line the flux level which, for an isotropic angular distribution and a 4-keV average energy, would correspond to a precipitating $O^+$ energy flux of 0.1 erg/cm$^2$-sec

It should be noted that the 11 storms utilized for this work had varying magnitudes and no attempt has been made to normalize the results to account for this. Each storm contributes to the data in two restricted local time intervals, so the detailed local time variations evident in the figures should not be interpreted as being representative of the local time variations in a single storm. It is significant, however, that extended regions of precipitating $O^+$ ions were seen in every storm and at all local times and that the median peak intensities on the nightside are roughly an order of magnitude more intense than those on the dayside.

## THEORETICAL AND RELATED EXPERIMENTAL RESULTS

The published theoretical work specifically directed toward interpreting the properties of the heavy ion fluxes in the energy range of these measurements is limited. Cladis (1973a,b) has proposed a mechanism whereby ionospheric $O^+$ ions are accelerated by resonant interactions with ion cyclotron waves generated by the ring-current protons. Palmadesso et al. (1974) have considered the ionospheric heating due to the electrostatic ion cyclotron tur-

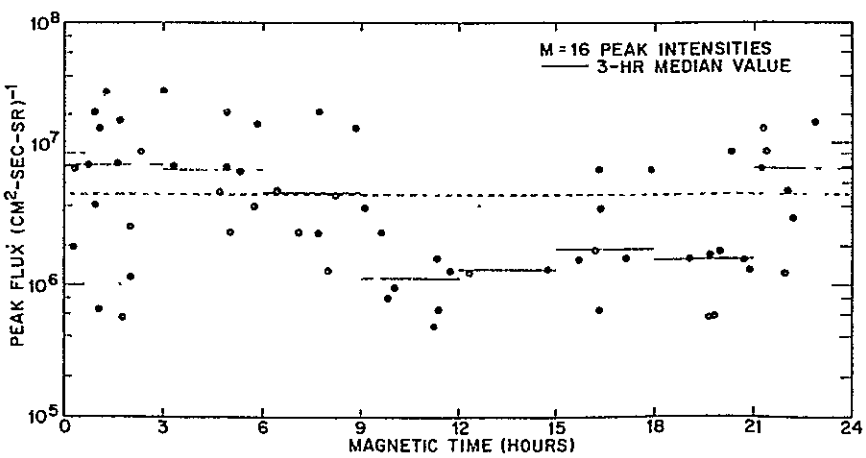


Figure 14. Peak $O^+$ fluxes observed during 11 major storms as a function of magnetic local time.

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bulence which is thought to be associated with the anomalous resistivity leading to field-aligned potential drops in the auroral zone. They suggest that this effect might contribute to the $O^+$ energization. Brice (1974) has shown how mixtures of heavy ions and protons in the ring current provide conditions where waves at frequencies below the heavy ion cyclotron frequency may be strongly amplified.

Torr et al. (1974) examine the atmospheric effects to be expected from the precipitation of the energetic $O^+$ ions. They conclude that large upward-moving fluxes of fast neutral oxygen atoms and atmospheric heating above 200 km altitude will result.

Berko et al. (1975) use a self-consistent calculational technique to compare the measured ion fluxes on Explorer 45 with the geomagnetic field deformation caused by these fluxes under the assumption that they are all protons. They set an upper limit of a few percent to the heavy ion contribution to the storm-time ring current at the time of the comparison. Simultaneous observations with the Lockheed energetic-ion mass spectrometer on satellite 1971-089A are not inconsistent with these results. The $O^+$ precipitation had fallen below the sensitivity threshold of the spectrometer at the time, late in the storm's recovery phase, when the comparison was made.

## SUMMARY AND CONCLUSIONS

The results now available on the $He^+$, $He^{++}$, and $O^+$ ions in the hot magnetospheric plasmas provide increasing evidence of the importance of mass and charge composition measurements for investigating the complex electrodynamic processes within and at the boundaries of the magnetosphere. The present measurements on these ions are still greatly limited in energy range, in mass range and resolution, and in detection sensitivities. The data have thus far been acquired only at low altitudes so there are not data in the equatorial plane to assess their importance to understanding processes in that region. Although still limited, the results from the energetic oxygen and helium measurements are beginning to provide sufficient definition of the characteristics of these particles that current theoretical models of the processes which act on them can be more realistically evaluated, but clearly more detailed theoretical work is needed.

Instrumentation is presently under construction for the GEOS and ISEE spacecraft and these instruments will have greatly improved mass resolution and sensitivity which will allow studies to be made of even rarer ionic constituents in the plasmas. The need for large-scale simultaneous observations of the energetic oxygen ions is evident and techniques for this type of observation should

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be pursued. Perhaps observations of the Doppler-shifted emissions from the precipitating ions could be used to differentiate them from the emissions of the ambient atmospheric constituents. All of the new techniques which can provide information on the composition of the hot magnetospheric plasma can be expected to be of increasing importance in future magnetospheric/ionospheric research.

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## APPENDIX D

# THE MORPHOLOGY OF ENERGETIC $O^+$ AND $H^+$ DURING TWO MAGNETIC STORMS

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(Presented at Washington, D.C. AGU Meeting, June 1975)

## ABSTRACT

A detailed study of the energetic $O^+$ and $H^+$ precipitation (0.7 keV $\leq E \leq$ 12 keV) in two magnetic storms has been undertaken utilizing the data from the Lockheed energetic ion mass spectrometer experiment on the satellite 1971-89A. The satellite was in an approximately circular and polar orbit at an altitude of 800 km in the local time plane 0300/1500 hours at the time of the measurements. An intensity parameter has been formulated for each ion species characterizing the integral precipitated energy flux in a traversal of the magnetic latitude range from $40^o$ to $80^o$. An intercomparison of these parameters on the day and nightside crossings shows that for both storms there is a large increase in the $O^+$ flux following the sudden commencement, with the flux intensity on the nightside significantly correlated with Dst. The nightside $O^+$ increase leads the dayside increase and lags the $H^+$ increase by over an hour in each case. Contour plots of the precipitating ion intensity versus time and magnetic latitude have been prepared and the overall average flux intensity and average ion energy have been computed in $2^o$ latitudinal intervals for each storm. These results will be intercompared and discussed.

# APPENDIX E

## SATELLITE OBSERVATIONS OF ENERGETIC $O^+$ IONS DURING TWO MAGNETIC SUBSTORMS

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(Presented at San Francisco AGU Meeting, December 1975)

ABSTRACT

Precipitating energetic (0.7 - 12 keV) $O^+$ ions during two substorms on 12 and 13 December 1971 have been investigated using data acquired with an energetic ion mass spectrometer aboard the polar-orbiting satellite 1971-89A. The satellite orbit was nearly circular at about 800 km altitude and in the local time plane 0300/1500 hours at the time of the measurements. The two substorms beginning at about 1500 hours on 12 December were fairly well isolated as indicated by the AE index and were wide spread in local time. The $O^+$ ions were observed in the morning sector from about 0200 to 0500 hours and the peak intensities were generally correlated with the AE index. The peak intensity observed was $2.5 \times 10^6/cm^2$-sec-sr and the mean width of the region of precipitation was 2.5 degrees in magnetic latitude. The mean position of the $O^+$ fluxes was always at a lower latitude than the "cutoff" trapping boundary for electrons with energies greater than 130 keV as measured on the same satellite.